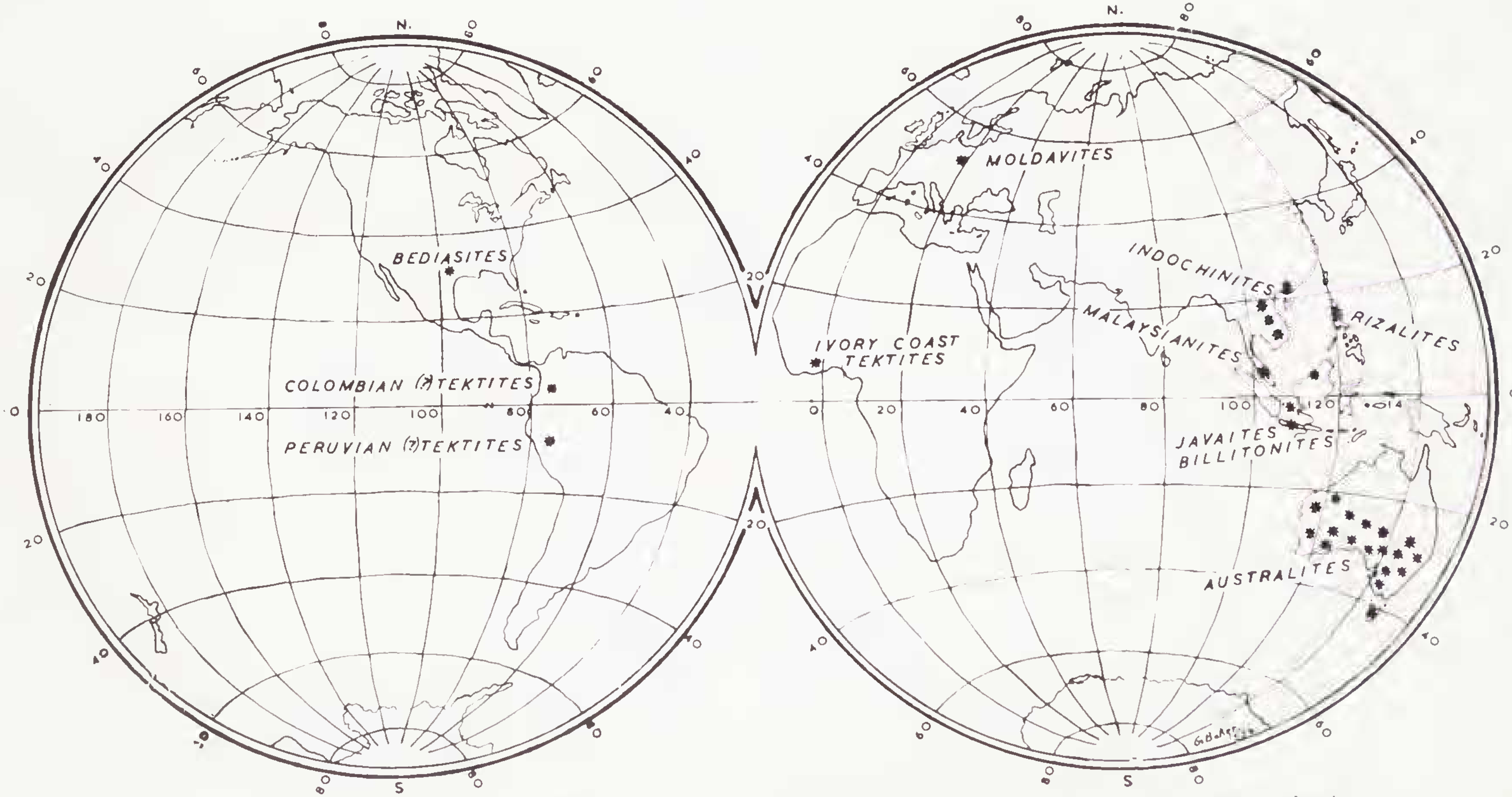
TEKTITES

by

George Baker, D.Sc. (Melbourne)



FRONTISPIECE.—The tektite strewnfields of the World on Lambert's Equivalent Azimuthal Projection.

CONTENTS

TEXT FIGURES

LIST OF PLATES

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AUTHOR'S PREFACE.

In this monograph it is endeavoured to bring together the more important and interesting facts and ideas concerning tektites. Stress has been laid more particularly on australites because of a closer acquaintance with them, and because of their unique shapes.

The literature dealing with tektites has grown considerably in the last two decades. Many articles by mineralogists, geologists and astronomers have appeared with the discovery of new types of tektites and additional centres of concentration within the strewnfields of types already known for over 100 years. The controversies prevalent concerning tektite origin and sculpture have also led to increased contributions from writers supporting their favoured theory of origin.

The study of tektites has reached a stage when, to quote Fenner (1940, p. 305)—" we should continue to accumulate facts, and to correlate them where possible. We should not suppress speculation and theory regarding their origin. Theories might well progress, step by step, with the accumulation of information ". Physical scientists and mathematicians have so far played a minor part in tektite studies, but may yet stimulate theories leading to the solving of certain problems peculiar to tektites.

The works of F. E. Suess, R. H. Walcott, E. J. Dunn, H. Michel, G. Linck, A. Lacroix, A. Rzehak, F. Berwerth, H. Otley Beyer, F. Heide, R. Janoschek, C. Fenner, L. J. Spencer, H. S. Summers, V. E. Barnes and others from among the extensive literature on tektites, have been freely drawn upon in the compilation of the chapters of this monograph.

The author is grateful to staff members of the Melbourne University Geology Department, particularly to Professor E. S. Hills who originally suggested that the work be undertaken, and to Dr. F. Loewe of the Melbourne University Meteorological Department, for valuable help and criticism, also to Mr. J. Spencer Mann for many of the photographic preparations. The former Director of the Victorian Geological Survey, Mr. W. Baragwanath, granted access to the Victorian Mines Department's files on australites, supplied valuable information upon many matters relating to tektites in Victoria, and kindly permitted certain illustrations to be reproduced from articles written by E. J. Dunn. Mr. P. W. Crohn translated several foreign papers on the subject-matter of tektites.

Thanks are due to M. K. Baker, E. Wall, A. J. Wall, R. E. Jacobson, E. D. Gill and others for their assistance in searches for australites in the southern portion of western Victoria.

The manuscript in its initial stages, was read and criticized by A. B. Edwards, D.Sc., Ph.D., D.I.C., and by the late H. B. Hauser, M.Sc., and in its later stages by Dr. M. H. Hey and Dr. W. Campbell-Smith of the British Museum of Natural History, London. The author is indebted to these gentlemen for their painstaking and constructive criticism, and to the Trustees and Director of the National Museum of Victoria for their help and encouragement in furthering this work.

CHAPTER I.

INTRODUCTION.

Tektites are natural objects of impure silica glass found in thousands on the surface of certain parts of the earth, and in places buried several feet beneath superficial deposits. They occur in widely separated regions and show minor chemical composition and physical variations from place to place. The name "tektite" ("tectite") was introduced by Professor F. E. Suess of Vienna in 1900, and was derived from the Greek word "tektos", meaning molten. The tektites are sometimes referred to as "Schmelzsteine" in Europe (cf. Winderlich, 1948, p. 110).

The origin of tektites has been a debatable question among scientific workers for over a century. Tektites, especially when broken, resemble glassy rhyolite-obsidian, but are not found in any obvious connexion with either recent volcanoes, or with older volcanic rocks. They seldom have much in common with other naturally occurring objects. Materials sometimes resembling them have been unnecessarily referred to as "pseudo-tektites". Some tektites are dull on the exterior from weathering, but many are bright and fresh in appearance because of protection from abrasion by burial in superficial deposits. This has led to much debate concerning the time of arrival of tektites upon the earth's surface.

Many theories have been elaborated, discussed and rejected in attempts made to unravel the mystery of tektite origin and to explain their sculptured surfaces. No completely proven and universally convincing theory has yet been established, so that several aspects of tektites are still very debatable. Most authors nowadays favour a meteoritic mode of origin, and Lacroix is probably correct in regarding tektites as extra-terrestrial homologues of the granitic rock types of the earth's crust. A few authors are still convinced that tektites were formed by terrestrial processes from terrestrial materials, some advocating artificial, some volcanic and others lightning modes of origin. It is hoped to show in these pages that an extra-terrestrial mode of origin is the most likely.

GENERAL DISTRIBUTION AND TYPES OF TEKTITES.

Tektites are distributed in several zones on the earth's surface (see frontispiece). In the European zone (fig. 1) they were discovered in the western divisions of Czechoslovakia (Moravia and Bohemia). A doubtful type recorded from southern Sweden has recently been rejected from the group of true tektites.

The Indomalaysian zone includes tektites from the Philippine Islands, Borneo, Bunguran Island in the Natuna Archipelago, Java, the Island of Billiton and the Island of Banka in the Dutch East Indies (fig. 2), southern China, Siam, French Indo-China and the Malay States (fig. 3).

The Australasian zone includes widely scattered centres of tektite concentration on the mainland of Australia (fig. 4), the Island of Tasmania (fig. 5), and other islands off the southern Australian coast such as Kangaroo Island, Lady Julia Percy Island, and the islands in Bass Strait (fig. 4).

In the African zone, tektites have been reported and described from the Ivory Coast region.

The American zone includes tektites from Texas and Georgia in North America (fig. 6), and the much discussed, still doubtful examples from Colombia and Peru in South America (fig. 7).

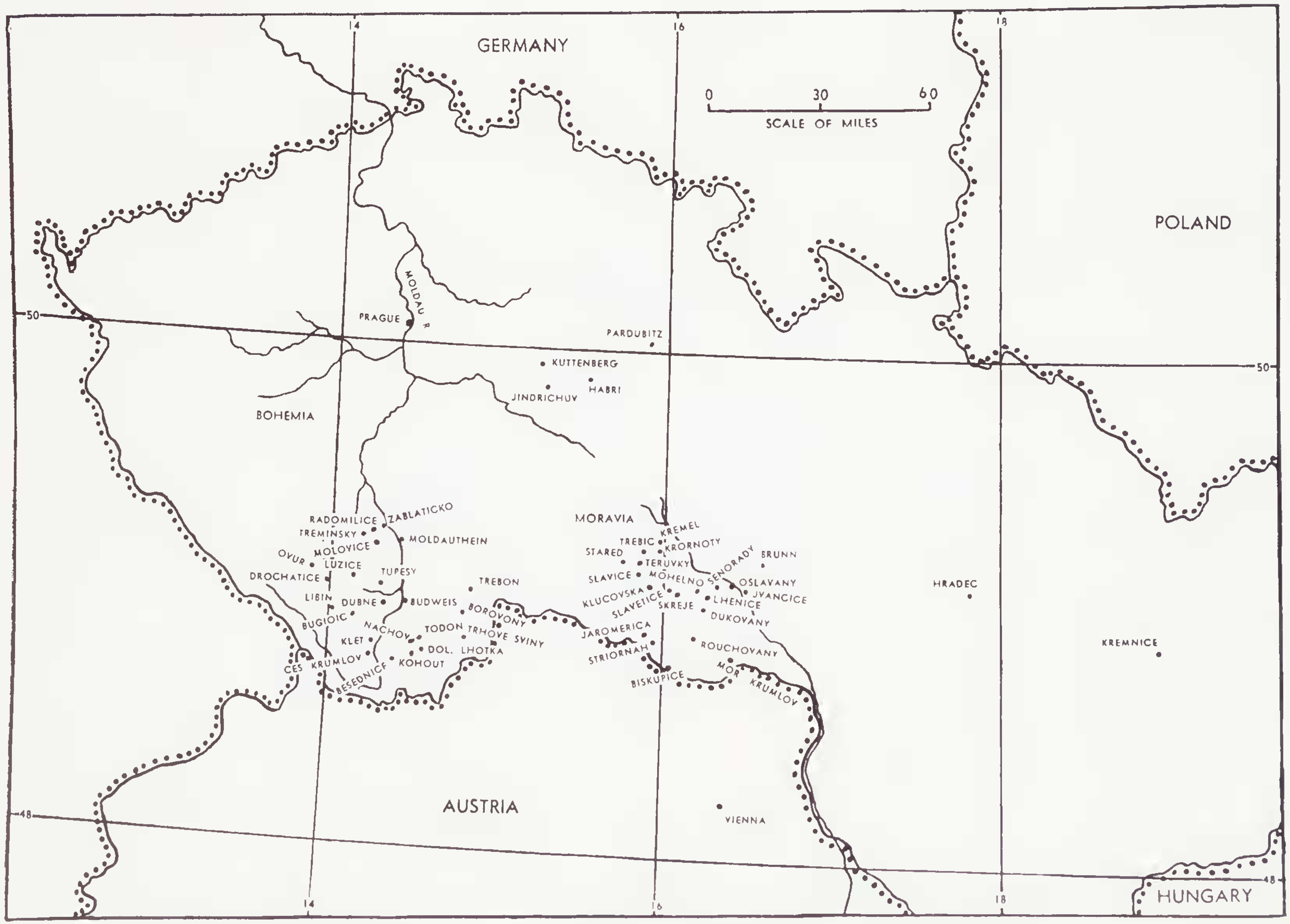

FIGURE 1.– Moldavite localities in Moravia and Southern Bohemia, Czechoslovakia.

Tektite nomenclature has, to a certain extent, followed the general principle used in naming iron and stony meteorites, when place names nearest the site of discovery are employed. As this scheme cannot be applied to each of the many thousands of tektites discovered in various strewnfields, whole groups are included under one name, according to their principal location upon the earth. There are eight recognized types of true tektites, and three still doubtfully referred to tektites.

Tektites from Australia, Tasmania and nearby islands, known since 1834, were first named *australites* by F. E. Suess (1900, p. 194).

Examples known since 1836 on the Island of Billiton, originally called " glaskögels " by the Dutch, are now named *billitonites* (van Dijk, 1879). They were referred to as " black diamonds " by Chinese alluvial miners in the Sunda Archipelago. The term *javaites* was applied to similar tektites found in Java (von Koenigswald, 1935).

The terms *indochinites* (known since 1928) and *malaysianites* were given to tektites from the Indo-Malaysian zone, and have occasionally been grouped under the general term *indomalaysianites* (Beyer, 1934). The Philippine Islands tektites, known since 1926, have been referred to as *rizalites* (Beyer, 1934) from the province of Rizal, Island of Luzon. Some authors retained the term " obsidianites " (Hodge-Smith, 1932, p. 581) for these tektites, but this term embraced tektites from several zones of distribution, and has now fallen out of use. Recent authors have introduced the term " philippinites " for these tektites.

In the European zone, tektites, known since 1787 from the western divisions of Czechoslovakia, are named *moldavites* after the original place of discovery—the Moldau River, Bohemia.

The American zone includes *bediasites*, named after the Bedias tribe of Indians in Grimes County, Texas, U.S.A. (Barnes, 1940a, p. 477), and the so-called *amerikanites* (Easton, 1921, and Martin, 1934), found in Colombia and Peru, South America. There is considerable doubt as to whether the amerikanites are really tektites. Since the Americas have a wide geographical extent, it has been suggested that the term " amerikanites " should be dropped (Barnes, 1940a, p. 492). Stutzer (1926) had suggested the name colombites (" kolumbiten ") for the Colombian glass, but stated later (Döring and Stutzer, 1928) that as this name had already been given to a mineral, he preferred to call them Colombian glass meteorites.

The recognized true tektites are—

Australites.
Bediasites.
Billitonites.
Indochinites (or malaysianites = indomalaysianites).
Ivory Coast Tektites.
Javaites.
Moldavites.
Rizalites (or philippinites).

Those at present regarded as doubtful tektites are—

Amerikanites (Colombian Glass Meteorites).
Macusani Glass, Peru.
Paucartambo Glass, Peru.

Those rejected from the group of the true tektites are—

Schönite (Skänite), Sweden.

Sakado Glass, Japan.

Darwin Glass (Queenstownite), Tasmania.

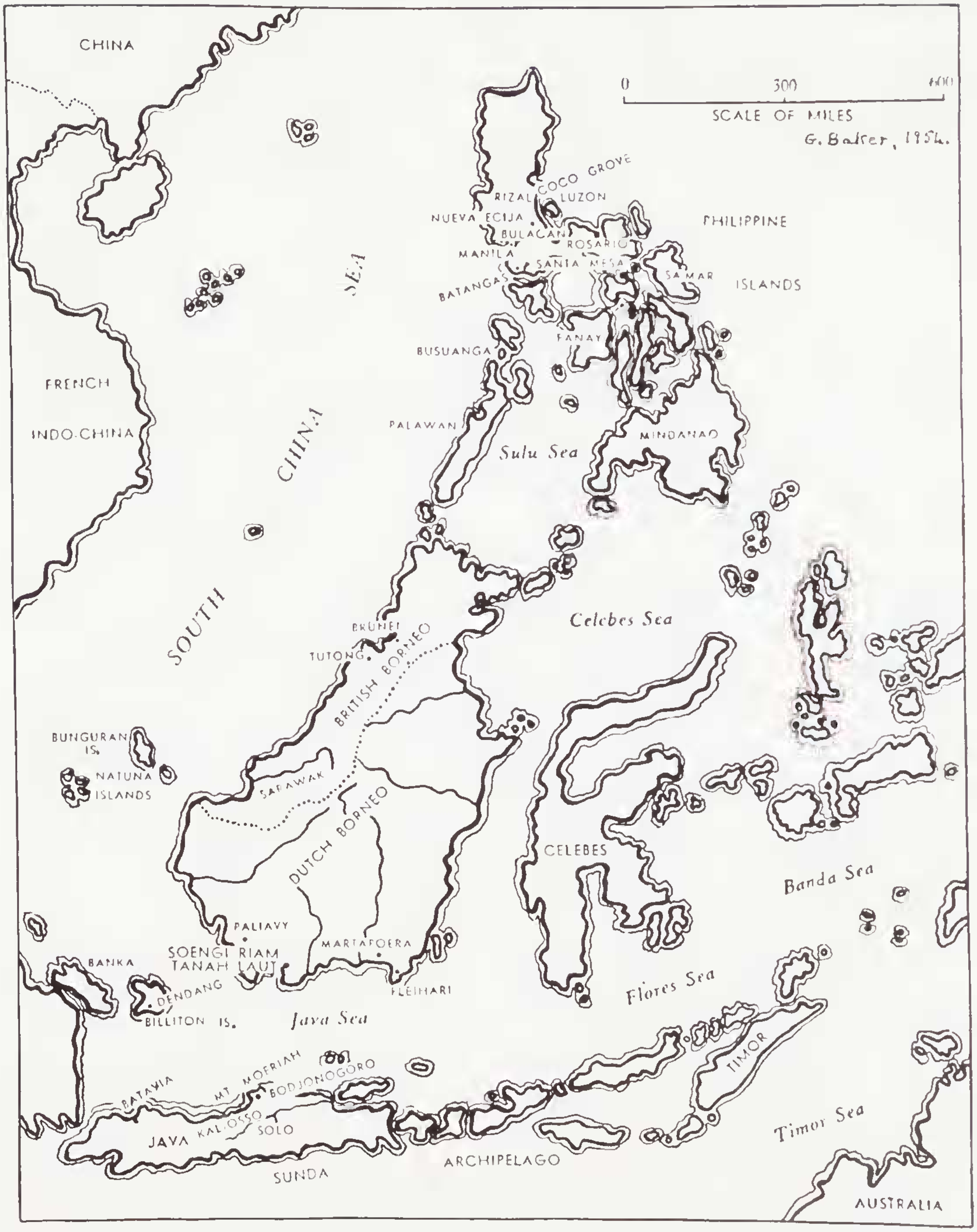

FIGURE 2.—Rizalite, billitonite and javaite localities in the Philippine Islands and the East Indies.

The glass from Hof Källna, southern Sweden, appears in the literature as *schönite* (Suess, 1914) and *skänite* (Aminoff, 1929). Only one piece was collected, about 1895-1896 by an engineer named Malte Akesson. It is translucent and brown in colour when held to a strong source of light, although coal-black in reflected light (Eichstädt, 1908, p. 323). Originally regarded as a tektite glass of cosmic origin, much doubt has been expressed concerning its authenticity as a tektite (Wiman, 1941, and Zenzen, 1940). In 1932, Lacroix wrote that schönite should be abandoned as a tektite, since F. Suess, the author of the term, had informed him the glass was an industrial product. Wiman (1941) concluded from chemical analysis (Table 15, column 30) that schönite was really bottle glass. It is thus evident that schönite now has to be discarded from classification with the true tektites.

Darwin Glass (Queenstownite) found in western Tasmania, where australites have also been recorded, bears no resemblance whatsoever to tektites in shape, colour, specific gravity, refractive index, and so forth, and by no means shows any similarity in its internal flow-line structures and lechatelierite particle content. It is more acidic than australites, contains less alumina, and shows other chemical differences, as well as marked differences in its melting temperature and coefficient of heat conductivity. Although it is by no means easy to advance conclusive evidence to show that Darwin Glass is not a true tektite, the evidence that is available points to such marked differences that in this monograph, Darwin Glass has been removed from the group of tektites, and is treated as a glass of uncertain origin in Chapter XVI.

The so-called tektite glass from Sakado, near Tokyo, Japan, weighs 470 grams and consists of a thin film of colourless glass covering white and dark coloured layers (Ohashi, 1936). The white layers are fine grained aggregates with $n = 1{\cdot}55$, the darker coloured layers are almost wholly colourless glass with $n = 1{\cdot}49$ and numerous pores. Fibrous mullite occurs as anastomosing streaks in the glass. Ohashi considered the rock was albite-quartz schist before fusion. The nature and chemical composition of this glass (Table 15, column 31) compare unfavourably with the characteristics of the true tektites, and the Sakado Glass is not considered as a tektite in this monograph.

MODE OF OCCURRENCE AND LOCATIONS.

The natural glasses recognized as true tektites occur loosely buried in superficial, generally incoherent deposits such as siliceous gravels, sands, clays and soils, or are exposed to the atmosphere in places where the superficial deposits have been subjected to not over severe weathering and removal. Very few tektites have been obtained cemented in secondary, superficial limestone, in manganiferous and hydrated iron oxide deposits, and in hardened old soil horizons of the Quaternary period.

The occurrence of tektites in any one part of a strewnfield, is generally haphazard, sometimes rather concentrated in certain parts, absent in other nearby parts or lightly sprinkled thereover. Numerous methods have been suggested to account for the scattered distribution of tektites over relatively wide areas in some of the strewnfields of the world. The several invoked means of dispersal depend largely upon the varying ideas relating to tektite origin.

Czechoslovakian Tektites (Moldavites).

The distribution of moldavites shown on maps prepared by Oswald (1936), is related to certain drainage areas, indicating spreading to some extent by stream action. The moldavites are distributed in two main areas (fig. 1),

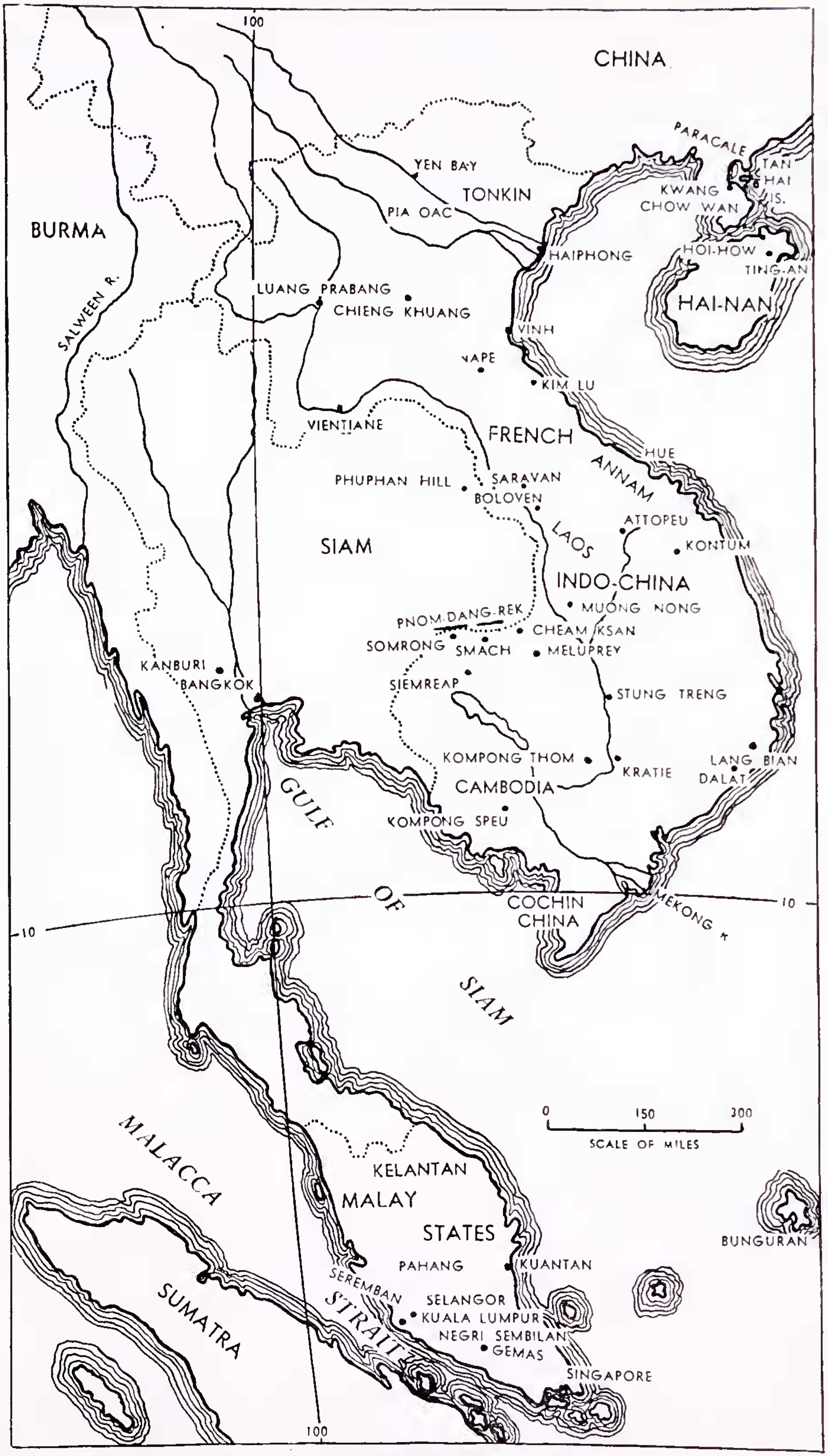

FIGURE 3.—Malaysianite and indochinite localities in Southeast Asia (after Lacroix, 1932).

namely in Moravia, extending from Oslavany to Trebic (Trebitsch), and in southern Bohemia, extending from Lhenice to Jindrichuv Hradec (Hanus, 1928), The total length of the area of spread is 150 kilometres and the areal extent 1,400 square kilometres. The largest and most beautiful moldavites occur at Skrey in Moravia (Janoschek, 1934 and 1937, p. 337) in deposits containing an assortment of pebbles from formerly extensive Jurassic sediments. They also occur in finer-grained sediments, in current-bedded shingles and in the Oncophora Sands (Late Tertiary).

Indo-Chinese Tektites (*Indochinites*).

Stream action has concentrated tektites into sands in Indo-China (Lacroix, 1932). The distribution of indochinites extends through Tonkin, Laos, Annam and Cambodia (fig. 3), an extent of 1,300 kilometres (about 770 miles) from north to south (Lacroix, 1930). In Annam, they were found as fragments on an old alluvial terrace, associated with ferruginous pisolites known locally as "bienhoa". Other discoveries include indochinites from old alluvium at Phuphan Hill, province of Nakon Panom in Siam (Lacroix, 1934) and from a district a few miles south of Muong Nong, province of Savannakhet in Lower Laos (Lacroix, 1935). The Muong Nong tektites occur under 1·05 metres of recent alluvium, in the upper 10 centimetres of an ancient lateritic clay. The concentration of these tektites in few regions, but over vast spaces, often in very large quantities, can only be due to stream activity if spread by terrestrial means, as they evidently have been to some extent. Their primary distribution, however, was most likely effected as a consequence of their fall to the earth's surface from outer space.

The indochinites in Lang Bian province, northern Cambodia, occur in swarms of twenty pieces over one square metre in parts, while elsewhere none occur in areas of 10 to 20 square metres. Indochinites from Pia Oac, west of Cao Bang in Upper Tonkin, and from Kam Phut and Van Phai in Tonkin, like those in northern Cambodia, occur in regions devoid of recent volcanism. They furnish all the forms met at Lang Bian in northern Cambodia and at Kwang-Chow-wan (Kouang-tchéou-wan) on the Chinese mainland. The substratum of the district consists of Palaeozoic limestones and mica schists, metamorphosed by the Pia Oac granite.

Elsewhere in Tonkin, indochinites occur in the military territory of Ha-Giang on the frontier of Kouei-tchéou, China. In the Phuphan Hill-Oubonne-Roi Et district, south-west of Savannakhet in Siam, the substratum is Triassic sandstone, and the tektites here cannot be separated morphologically from those of Cambodia, where they are known in the Prek Chlong, between Kratié and Snoul, and other localities in the provinces of Stung-Treng, Siem Réap, Kompong Cham and Phnom-Penh.

In Laos, tektites occur at Ban Houei Nong, east of Ban Sat on the Mekong River, and Ban Houei Hai on the left bank of the Mekong River, province of Xieng Khouang. They are also found near Napé in the province of Cammon and in the provinces of Savannakhet, Saravane, Attopeu and Bassac.

Indochinites in southern Annam are found at various localities in the provinces of Kontum, Pleihu, Darlac, Phu-Yen, Haut Donnaï and Binh Thuan (Phan Thiet) (Saurin, 1935). In northern Annam they occur in the provinces of Nghé-An and Ha-Tinh, and in Cochin-China they have been discovered in the province of Tay Ninh. All came from within or near the surface of alluvium, beneath which the substratum varies from gneiss, mica schist, granite, Palaeozoic metamorphic schist, andesite and Permo-Triassic sandstone, to ancient

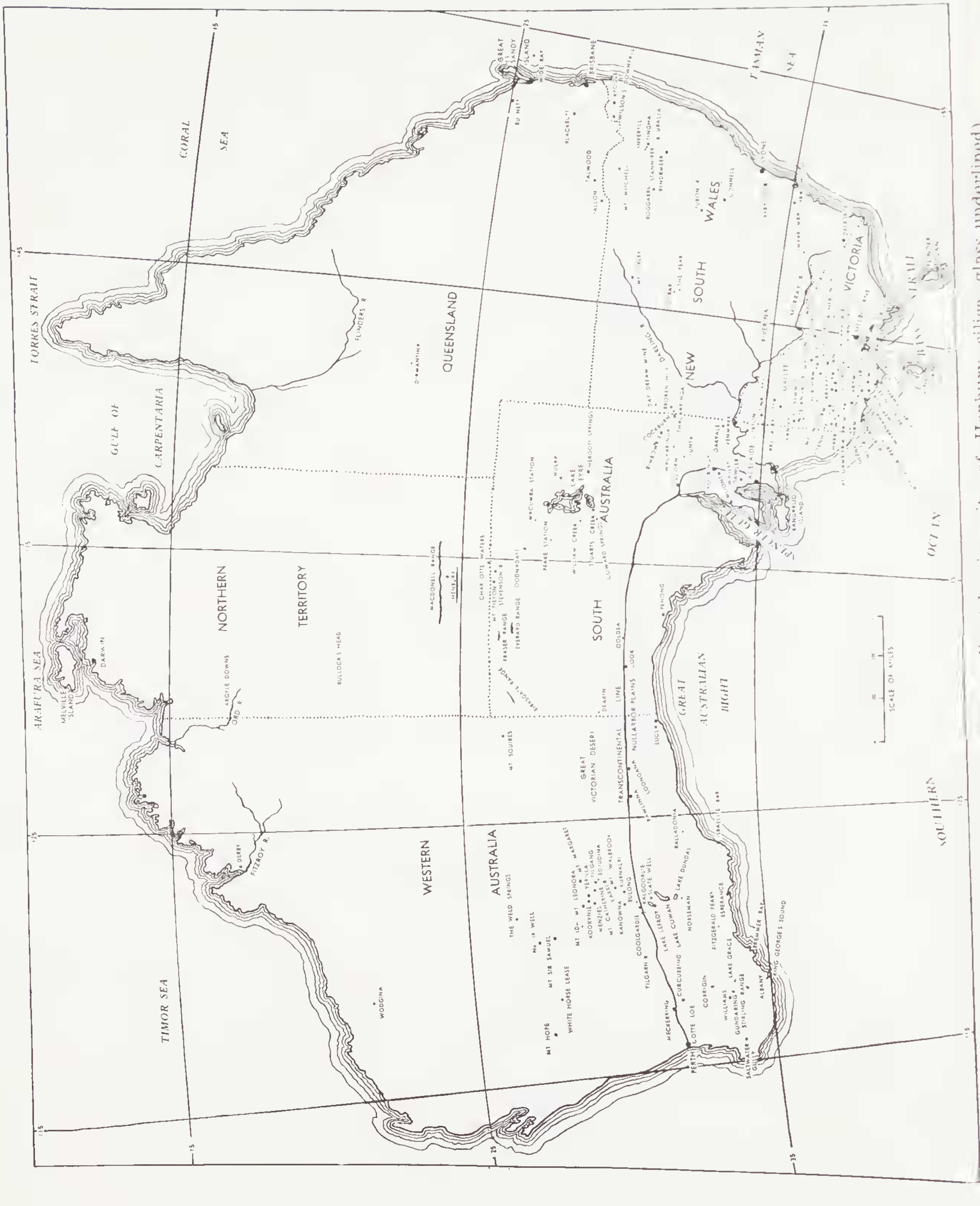

FIGURE 4.—Australite localities in Australia (showing site of Henbury silica glass underlined).

dacites and both Tertiary and Quaternary basalts. The indochinites here thus show no relationships to the country rocks, and are not connected in any way with the eruptive rocks, contrary to the local opinion that they are basaltic glasses (despite their acidic chemical composition). Saurin did not find any indochinites in the recent alluvium; all his specimens came from lateritized old alluvium, just as on the Lang Bian plateau, where the old alluvium is up to 2 metres thick in depressions.

In the Smach district, at the foot of the Dangrek massif, the tektites are accompanied by large crystals of zircon (Lacroix, 1929), in a yellowish-clayey soil rich in ferruginous pisolites (" beinhoa ").

Hai-nan Tektites (Indochinites).

On the island of Hai-nan (fig. 3), M. Essertau found tektites near Séan-Tô, Wentchang district, west of Hoi-how, where they were concentrated over an area of some 400 to 500 square metres, under sandy humus 0·3 to 1 metre thick that covered white kaolin clay of granitic origin (Lacroix, 1934). They occur in great abundance at the surface of this clay. Similar indochinites have been found at Sim San, district of Ting-an, Hai-nan island, like others unearthed by M. Jabouille to the east and west of the Matché River in Potao, Kwang-Chow-wan and south-west of Fort Bayard near Lake Surprise, north-west of Potsi in the same district on the Chinese mainland.

Malay Tektites (Malaysianites).

Tektites occur in Malaya (fig. 3) in alluvium along the Blat and Gambang valleys of Kuantan, also at Sungei Lembing in Pahang at Sudu near Seremban, at Gemas, in parts of Ulu Selangor and on the Triang River (Scrivenor, 1931).

Philippine Islands Tektites (Rizalites).

In 1926 and at intervals thereafter, tektites known as rizalites were located in various provinces of several islands comprising the Philippine Islands (fig. 2). On Luzon, they are abundant and occur in the following provinces: Western Pangasinan, Zambales, Nueva Vizcaya, Nueva Ecija, Rizal, southern Bulacan, Batangas, Camarines-Norte and Camarines-Sur (Beyer, 1934). On Samar, one occurred in the Barrio of Lawaan, Wright. On Busuanga, several were scattered about the province of Palawan. Only a few specimens have been reported from Panay, where they were ploughed up in the Aklan district of Capiz province. On Mindanao, several have been reported from placer mines in Surigao and north-eastern Agusan provinces.

One of the richest and largest known tektite deposits in their natural environment is in the Philippine Islands (Beyer, 1940). Typically indochinites occur in south China and north and central Indochina, but a few tektites regarded as similar to indochinites also occur sparsely in Luzon, Philippine Islands. The principal types in the Philippines, however, are rizalites which occur largely in Luzon, and they come from shallow beds of red laterite, placer mines (cf. Winderlich, 1948, p. 112) and from yellowish- or reddish-coloured gravel-filled soils, especially in the Santa Mesa tektite site, where the gravel overlies adobe (volcanic tuff). Three hundred rizalites discovered by Beyer during archaeological investigations at Novaliches, on a pre-historic site attributed to the Iron Age (500 years before our era), and others from Nueva Ecija and Batangas, all occurred in alluvium as in Indo-China and on Billiton Island (Lacroix, 1931a). Those in the province of Batangas were obtained from Rosario, about 20 kilometres from the Taal volcano.

Java Tektites (Javaites).

Javaites are mainly confined to central Java (fig 2). A few tektites similar to the javaites, however, occur in the Santa Mesa district of Rizal, Philippine Islands.

FIGURE 5.—Australite localities in Tasmania (showing sites of Darwin Glass underlined).

The javaites have been included with the general group of the indomalaysianites, along with billitonites and malaysianites, but they are not as widespread, and it is the group of the billitonites and malaysianites (which includes the indochinites) that occupies the greatest area of all the Far Eastern

occurrences. Beyer divided the indomalaysianites into four groups on the grounds that they all show characteristic differences in shape, surface markings, flow lines and the degree of viscosity of the original material.

Billiton Island and Borneo Tektites (Billitonites).

The tektites on the island of Billiton (fig. 2) have been concentrated into tin-bearing gravels by stream action (Hövig, 1923), and also occur in stratified Quaternary tuffs (Verbeek, 1897).

Tektites from Tutong Station, near Brunei township, Borneo (fig. 2), were washed out of sand that forms a well-marked terrace of Diluvial age (Mueller, 1915). Some of the Borneo tektites occur in gold and platinum mines on the south-eastern portion of the island of Borneo (Verbeek, 1897).

Australian and Tasmanian Tektites (Australites).

To aboriginal man has been credited the distribution of certain australites (Tate, 1879, p. 70, and anon. in Nature, 1934, p. 605). Tate's theory that the scattering of " obsidian buttons " (i.e., australites) in South Australia, had been effected by human agencies, was admitted as due to the wish perhaps being father of the thought, inasmuch as the only feasible explanation of their presence by natural causes, militated against his theory of origin for what he called the " loess " in South Australia.

That the aborigine used " obsidian buttons " as articles of barter, and thus distributed them far and wide over Australia, was accepted by F. M. Krausé (1896, p. 214). The fact remains, however, that the aborigines had first to find the australites, for they had no means of manufacturing them. So that even if the aborigine did carry around and ultimately drop some australites in a different place from that in which they were found, he was not responsible for the present scatter across the Australian continent. Stephens (1897 and 1902) was convinced aborigines distributed " obsidian buttons " over the mud plains of Victoria and the Riverina, but thought no such explanation applied to those found in quartz drift in Tasmania. The occurrence of " obsidian buttons " at depths of 18 feet in stanniferous and auriferous drifts in Tasmania indicates the impossibility of distribution by natives, according to Twelvetrees and Petterd (1897).

Ice has also been invoked as a means responsible for australite distribution. Scoular (1879, p. 68) first suggested that the Australian tektites were distributed by icebergs, and later on, it was opined that the irregular distribution of " obsidianites " in the Dundas area of Western Australia, was not due to sub-aerial agencies, but to drifting ice from Antarctica (Campbell, 1906, p. 22). The idea put forward in this connexion was that the snow-coated ice sheet of Antarctica would afford a soft bed on which the " obsidianites " would fall and cool. Ice floes then drifted to Australian shores, the stranded ice melted, depositing the " obsidianites." Tate (1879, p. 70) quite rightly disagreed with this theory of " obsidianite " transport by icebergs from Mt. Erebus and Mt. Terror in the Antarctic. Recent expeditions to the South Polar regions have so far reported no tektites connected with the ice sheet.

Advocates of tektite distribution in Australia by means of wind and volcanoes (Twelvetrees and Petterd, 1897, and Dunn, 1912) believed in a terrestrial mode of origin for the tektites. Dunn (1914, p. 325) thought the probable distribution of australites was southwards from the great volcanic area of Western Victoria, towards Tasmania, and in a north and west direction

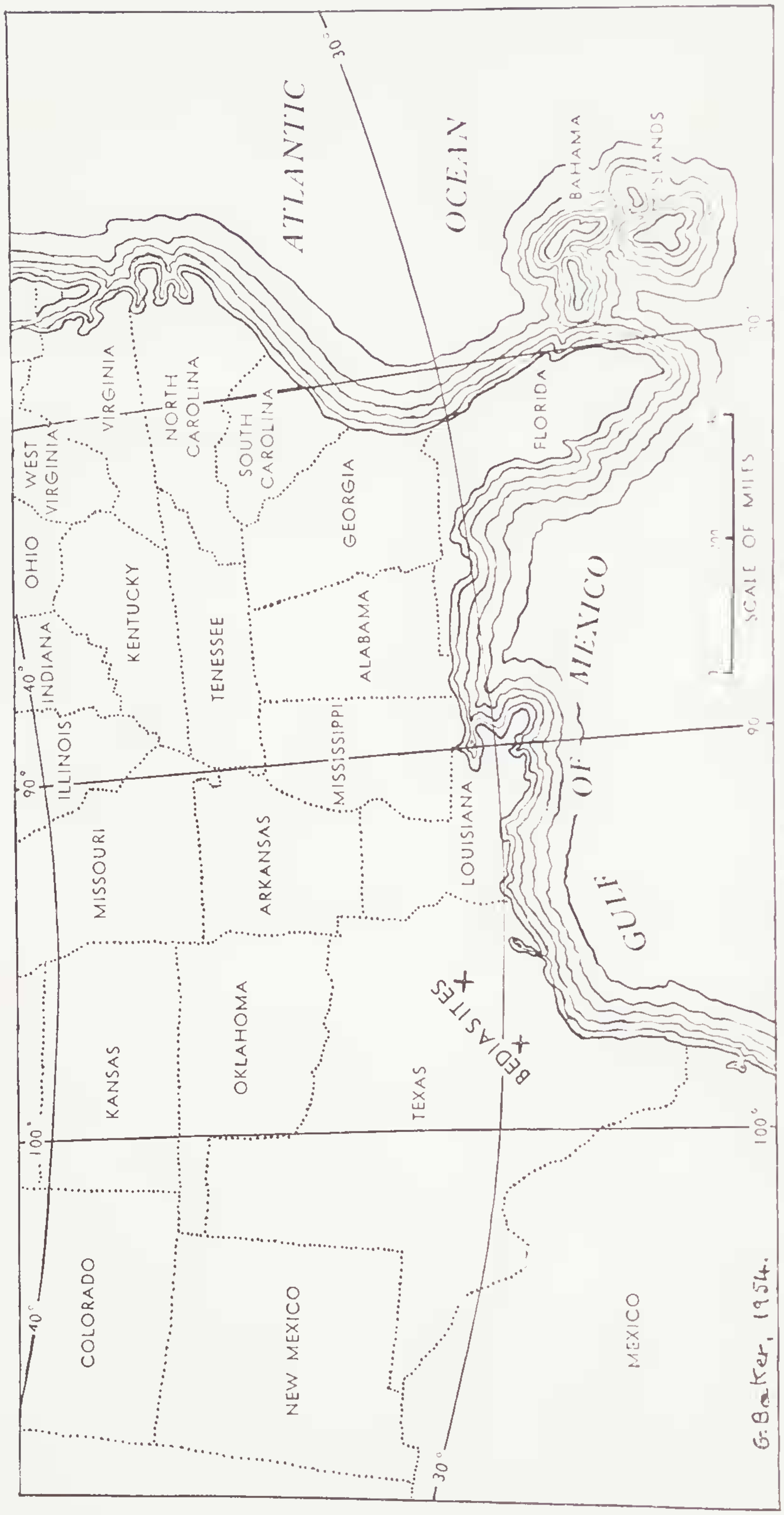

FIGURE 6.- Bediasite locations in Texas, U.S.A.

to South Australia and Western Australia south of the South Tropic, the westward trend being governed by the direction of high altitude air currents, but there is no support for this postulate.

As Selga (1930, p. 25) commented, no one who has seen the size and markings of tektites, could seriously consider the hypothesis of dispersal from volcanoes to non-volcanic areas by such transportation as amulets by primitive man, gizzard stones by birds, glacial deposits by ice sheets, pebbles by water, or as small volcanic bullets shot out by volcanoes.

Since the Nullarbor Plain stretching from South Australia into Western Australia, where many australites are found, is an uninhabited, monotonous limestone plain without watercourses, the suggestion that australite distribution was carried out by running water or by aborigines, receives no support (Fenner, 1934, p. 64). The facts of australite distribution strongly support the belief held in Australia, that most australites are generally found approximately where they originally fell. Some certainly have been carried around by aborigines and as gizzard stones by large native birds, and some have been concentrated into placer deposits by running water, but these are largely of local importance only, and scarcely affect the overall distribution across 2,000 miles of the continent. It is thus apparent that neither aborigines, glaciers, icebergs, streams, birds, winds nor volcanoes adequately account for tektite spreading over the vast areas where they are known. Moreover, no primary sources for such distribution have been located on any part of the earth's surface. In Australia (fig. 4), tektites are spread over 2,000,000 square miles of the continent as a conservative estimate. They are found on mountain tops, on the surfaces of vast plains (both volcanic and sedimentary), in desert sand dunes, in clay pans and creek beds, buried deep (20 to 30 feet) in alluvial deposits* and less in shallow surface soils. In the Australian tektite zone, it is thus necessary to invoke an extra-terrestrial method to account for such an extensive vertical and lateral distribution. Certain centres of concentration within the vast strewnfield in Australia occur in auriferous and other gravels, as in various parts of New South Wales, Victoria and Tasmania, and some occur at various depths in the clay pans of the more arid regions. Such concentrations are best explained in terms of local stream action. Other centres of relatively abundant concentration occur at Mulka, Oodnadatta and William Creek in South Australia, at Port Campbell and Nirranda in Victoria, at Charlotte Waters in Central Australia, at Kalgoorlie in Western Australia and on the Nullarbor Plain. The occurrences at all of these places are not satisfactorily explained by stream action, and at all events, there has to be a primary source from whence streams and rivers could derive the many thousands of australites known—such sources do not exist on the surface.

In parts of Australia, the australites are scattered over considerable areas. Although there are concentration centres in the Nullarbor Plain region, there are also vast areas of this plain where the scattering is widespread (Fenner, 1934, p. 63). Also, occasional australites have been located in the Mallee scrub areas of north-western Victoria (Armitage, 1906, p. 100), and on the surface of uncultivated land in plain country 50 miles north-west of Mt. Wycheproof, as well as scattered occurrences throughout the volcanic plains of the Western District of Victoria. Other sporadic occurrences are in sand dunes in the Great Victorian Desert, in the Fraser Range and elsewhere in Central Australia (Streich, 1893). Two found at Stuart's Creek, Lake Eyre, were recorded as

* One abraded australite core was found at the bottom of a shaft 125 feet deep in the North Lead at Kanowna in Western Australia, but it is uncertain whether the specimen was *in situ*.

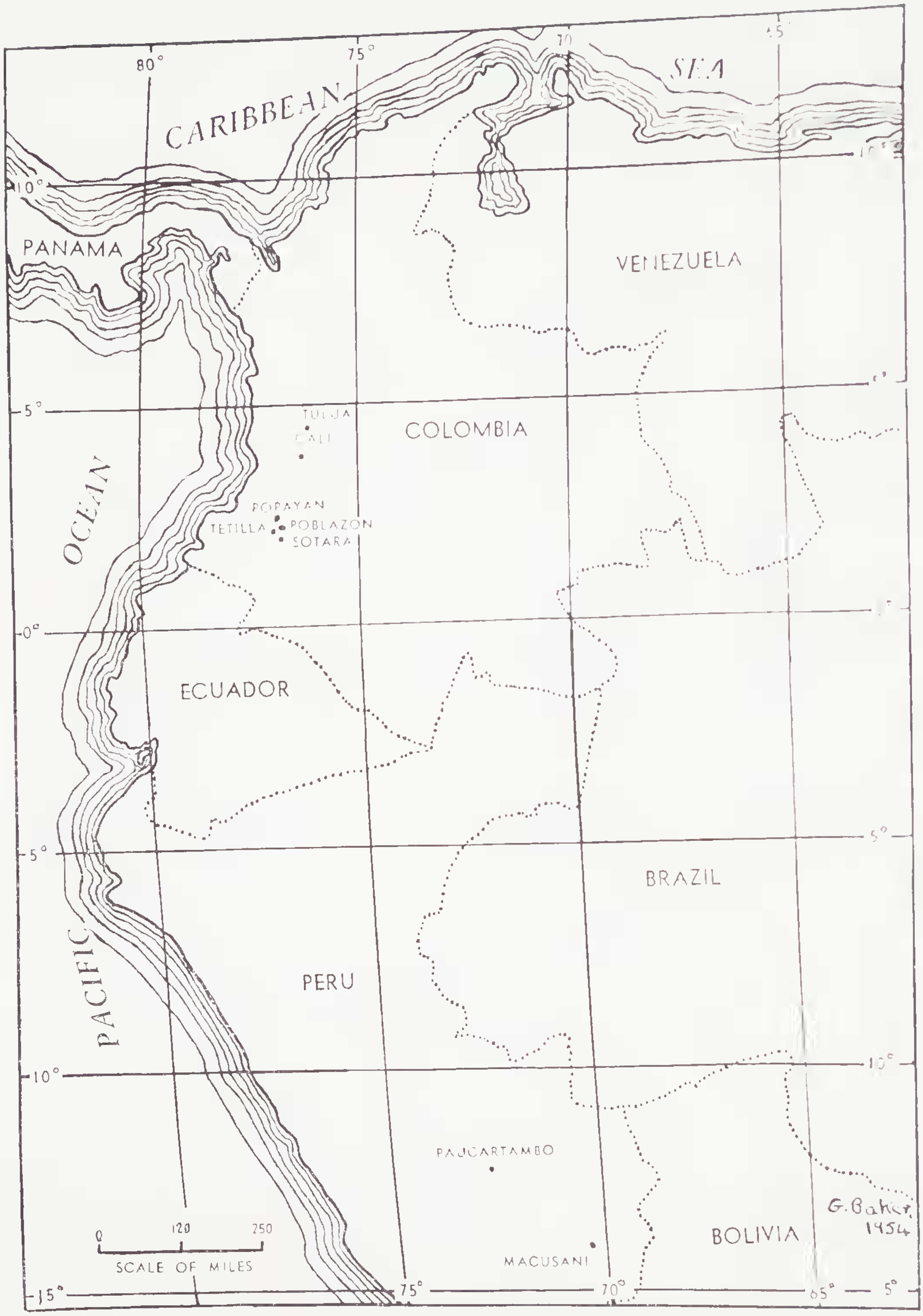

Figure 7.—Localities of the (?)tektites of Colombia and Peru in the north-western portion of South America.

types of " obsidian bombs " that occur in so many parts of the centre of Australia (Moulden, 1896), while Woodward (1894, p. 34) had stated earlier that " obsidian bombs " were scattered all over the interior of Australia and over a large area in Western Australia. " Obsidian buttons " were also recorded from alluvium as well as on the surface, most frequently on the stony downs and table hill country of the far north of South Australia, far distant from any volcanic rock (Brown, 1893, p. 25). Others were recorded as appearing loose on the surface and embedded in " crust limestone " in South Australia, one from Gawler being in the centre of a travertine nodule (Tate, 1879, p. 70).

Few have been recorded from the more northerly portions of the Australian continent. In the Northern Territory, Mr. Wm. Laurie reported the common occurrence of " obsidian bombs " from Bullock's Head, about 40 miles from Tanami on the Granite road (Jensen, 1915).

In Tasmania (fig. 5), australites come from tin drifts at Thomas Plains in the north-east, 10 feet below the surface at Long Plain, near Waratah, in the Norfolk Range, and in auriferous wash from Camden Plain, Mt. Barrow and Lisle. They are also reported from quartz wash overlain by 2 feet of alluvium at Springfield, and from clay at a depth of 5 to 6 feet near Weldborough (Thomas Plains). Specimens are also known from Back Creek in Tasmania, and from King Island in Bass Strait.

Australites have been found in many parts of Victoria, principally in the western half of the State. In 1925, an australite button was found by A. J. Templeton in a gravel pit at Victoria Valley near Dunkeld. At Maldon, one was found in the Porcupine Lead under 4 feet of alluvium, while in Fletcher's Shaft, Rocky Point Lead, Grampians, one was found on bedrock, buried beneath 23 feet of alluvium. Examples naturally concentrated in auriferous wash-dirt from the Mt. William goldfield, occurred in abundance in Mason's Gully and its branches, and were even more abundant in Neild's Gully and Jimmy's Creek (Dunn, 1912a). Many others have been discovered on the surface throughout the western half of Victoria, but apart from concentrations at the places already mentioned, they occur as a few or as single specimens only at Napoleons, Nerring, Grassmere, Birchip, Caramut, Telangatuk East, Rokewood, Polkemmet East, Mt. Eccles, Mt. Elephant, Mt. Mercer, Mt. Talbot, Beulah, Mt. Leura, Nhill, Pink Lake, Byaduk, Skipton, Willaura, Ararat, Maroona, Boort, Boulka, Cudgee, Warracknabeal, Kewell, Hochkirk, Terang, Mortlake, Colac, Horsham, Harrow, Warrnambool, Portland, &c. A few come from the Otway Ranges as at Beech Forest, Moonlight Head and Glen Aire. Two or three are also known from Torquay and Ocean Grove. The greatest concentrations in Victoria, apart from those in alluvial deposits at Stony Creek, Victoria Valley and others mentioned above in the Grampians region, occur at Port Campbell and at Nirranda on the south-west coast, where approximately 2,000 have been found. Other occurrences in Victoria are indicated on the map, figure 4. Very few are recorded from the eastern half of the State, as near Wonthaggi, &c.

The first recorded tektites from Queensland were found by Mr. H. P. Leahy at Newinga Resumption, between Thallon and Talwood, on the Goondiwindi–Thallon railway line, parish of Guarardera (Dunstan, 1913). Several were later found by miners at a depth of 6 feet in a prospecting shaft west of Blackbutt, county of Cavendish, district of Morton.

Several australites were recorded from New South Wales and South Australia by Card (1903, p. 218). Among those from New South Wales, one from Liverpool was discovered during ploughing operations, one from Braidwood

was in alluvium, and another from alluvial gold workings at Bull and Damper Creek, Quartzville, near Tumbarumba. Beautifully preserved "curious little button-shaped bombs of black obsidian" (i.e., australites) were said by Card (1902) to be scattered over the surface or entombed in alluvial drifts all over Australia. The well-preserved character of specimens from Uralla in New South Wales, was ascribed to their falling into water and burial under a protective alluvial cover. A "beetle-shaped" specimen from Cross Roads, Liverpool-road, New South Wales, which resembled the one ploughed up at Liverpool, was picked out from the clay bank of a road cutting in 1912 (Card, 1919). It was originally thought that australites in New South Wales were confined to an area bounded by Bendemeer and Tingha (Smith, 1926). This is an area of 60 square miles, specimens being recorded from Mt. Mitchell, Watson's Creek at Bendemeer, Cockburn on the New South Wales–South Australian border, and Day Dream Mine in the Barrier Ranges. All of the recorded specimens were on or near the surface, the deepest being 8 feet below the surface. There are other occurrences known from other parts of New South Wales. An "obsidian bomb" from O'Connell, near Bathurst, was found at a depth of 20 feet when sinking for gold (Baker, 1900). In addition, a few specimens are also known from Traveller's Rest, White Cliffs, Lake Victoria Station and Avoca Station near Wentworth, Popiltal Station on the Darling River and Mt. Oxley. Other places where australites have been located in New South Wales are shown on figure 4.

Tektites identical with those from Australia, are occasionally exhibited in placer mining camps in the United States of America (La Paz, 1938). Persistent questioning disclosed that they had been brought in by miners from the tektite sprinkled goldfields of Australia (Barnes, 1940a, p. 477).

Texas Tektites (Bediasites).

The bediasites from Grimes County, Texas, United States of America (fig. 6), occur associated with siliceous gravels a few inches thick in an elliptical area 5 miles wide and 10 miles long. The gravels, of Pleistocene age, rest on bedrock consisting of shales, sandstones and lignitic clay comprising the Jackson Formation of Eocene age. These tektites may have been spread out by stream action (Barnes, 1940a, p. 552). A single bediasite from De Witt County, 130 miles south-west of Grimes County, may have been transported there by man. Later discoveries of bediasites (Barnes, 1951, p. 1422), are from Muldoon in Fayette County and from Gonzales County, where, as in Texas generally, these tektites may be weathering out of the upper part of the Jackson Formation (Upper Eocene).

African Tektites (Ivory Coast Tektites).

In the Ivory Coast region of West Africa (see frontispiece), tektites occur sparsely to a depth of one metre in gold-bearing quartzose alluvial deposits near the village of Akakoumoekrou (Ouellé subdivision), on the Comoé River, and in such places within a radius of Ouellé as Amoroki (Kongoti), Bayassou (Kodi), Anoumbo, Daoukro, Gagou, Dékikrou and Agni-Assikasso (Lacroix, 1934). They occur in an area devoid of recent volcanism, where the bedrock is granite and crystalline schist.

South American (?)Tektites (Colombian and Peruvian (?)Tektites).

In Colombia, South America, (fig. 7), glass balls described by Humboldt (1823, p. 433) as obsidian, and suggested to be tektites by Codazzi in 1916, but later considered by him as volcanic (i.e. terrestrial volcanic), are found in large numbers on or near the surface, on hills and in valleys over an extensive area near Cali (Stutzer, 1926, Döring and Stutzer, 1928).

Stutzer (1926) did not believe the Colombian glass spheres were volcanic obsidian, because of their distribution over 300 kilometres, extending from the Popayan region, through Cali to Tulua, because the deposits there were all superficial or young deposits, and because the Indians called them "piedras de rayo" (implying the idea of derivation as stones from lightning). He thought the glass spheres were distributed by the River Cauca and the headwaters of the Patia River. Friedlaender (1927) was convinced the Indians had spread them about, and disagreed with Stutzer's claim that the glass spheres were not obsidian. He maintained that inclusions in the glass were similar to those in pumice, while the specific gravity of the glass was identical with that of obsidian. Splinters of the same kind of glass occur abundantly at Tetilla near Popayan (Stutzer, 1926).

The glass is found near volcanoes and in non-volcanic regions (Codazzi, 1929). The spheres, first noticed by Humboldt and later by Küch and Bergt, W. Reiss and A. Stübel, and by J. M. Zujovic, were described by Humboldt as resembling tears or balls with rough surfaces, thrown out by Sotara volcano, near Popayan. Humboldt also found dense black to colourless glass resting on basalt at Los Serillos, Uvales and Palacé, but altogether foreign to this rock. Martin (1934) concluded that the glass objects from Colombia and Peru, known as "amerikanites", were "obsidian bombs" (name erstwhile used for australites) rather than tektites. Michel (1939) also thought these glass spheres were obsidian.

The Peruvian tektites came from Macusani and Paucartambo, south Peru (fig. 7). The tektitic nature of the glass from Paucartambo (Linck, 1926, p. 157), was doubted by Dittler (1933). In reply to Dittler's criticism, Linck (1934), stated that only people who had not seen the Paucartambo tektite could doubt its authenticity as a tektite, since its shape, nature and surface features agreed perfectly with those of other tektites.

Comments on Distribution and Mode of Occurrence of Tektites.

The recorded mode of occurrence and suggested methods of tektite distribution, indicate their presence within or resting upon superficial deposits with which they have no common relationship beyond field occurrence. No primary source has yet been found upon the earth's surface, that would supply material for distribution according to theories advocating dispersal by stream action, or by other terrestrial agents for that matter. No tektites have been found as constituents of any terrestrial rock in which they could have been generated upon the earth's surface or below its surface. The superficial deposits that contain tektites, are of such a nature that tektites could not have been generated within them. These superficial deposits overlie rocks of very diverse character and age, such as granite, dacite, basalt, tuff, clay, mudstone, sandstone, various kinds of limestone, marble, schist, gneiss, &c., of Silurian, Devonian, Carboniferous, Triassic, Tertiary and Pleistocene to Recent age. Some of the Australian tektites rest on superficial deposits overlying Pre-Cambrian rocks. Tektites are thus undoubtedly alien to the country rocks of all regions where they have been discovered.

The geological ages of the superficial deposits in which the various groups of tektites have been found, are referred to in Chapter VII in further detail. These deposits range in age from Tertiary to Recent. It is accepted that the tektites are younger than the bedrock upon which they and the containing superficial deposits rest, and that they are a little older or approximately the same age as the superficial deposits, as far as their time of arrival upon the

earth's surface is concerned. They would be older than the superficial deposits if washed into them, but younger if they fell to earth upon such deposits. No detailed study has yet been carried out relating the tektites in each strewnfield with the geomorphology of the old erosion surfaces on which the tektite-bearing superficial deposits occur.

COLLECTING AND COLLECTIONS OF TEKTITES.

The first tektites collected for scientific purposes came from the Moldau River in Czechoslovakia in 1787. The first publication concerning them was prepared by Professor Joseph Mayer (1787), and they were later analysed by Dufrenoy (about 1844). The first moldavites from Trebitsch in Moravia, were collected for study by Dr. F. Dvorsky (1883, p. 219). They had previously been collected by the Bohemian peasants, who referred to them as "bouteillenstein" (bottle-stones) on account of their bottle-green colour, and as "schmucksteinen" (decorative stones). They were earlier thought to be artifacts (Breithaupt, 1823, p. 223). Five to six thousand moldavites were collected *in situ* from Moravia and Bohemia by Hanus (1928), and ten thousand were stored in the National Museum Collection at Prague (Kaspar, 1938).

In the Santa Mesa tektite site, Philippine Islands, Beyer collected over 200 tektites and 150 tektite-like bodies (comparable with "amerikanites") within an area of five square metres, after the upper soil layer had been skimmed off to a depth of 30 centimetres. A few Philippine tektites were also collected from gold washings at Coco Grove, province of Camarines-Norte, Luzon (van Eek, 1939).

In French Indo-China, tektites could be gathered in thousands from soil (Lacroix, 1932). In their abundance, they excelled all previously proved tektite occurrences. For example, 362 complete forms and 2 000 fragments were collected from parts of Lower Laos (Lacroix, 1935), and 1,750 from Smach in northern Cambodia (Lacroix, 1929). A large lump weighing nearly 2 kilograms was found in Muong Nong province, F.I.C. by a native woman searching for edible roots.

Two of the best tektites from Malaya were discovered, without labels, in the Raffles Museum, Singapore (Scrivenor, 1931). They are believed to be from Kelantan, and were later presented to the British Museum of Natural History.

Bediasites were first collected for scientific study between April, 1936 and December, 1938. 482 pieces were obtained from gravel deposits by the personnel of a mineral resource survey, who referred to them as "obsidian spats". The local residents had collected samples for up to thirty years previously; the glass had probably been known for fifty years up to the time it was described in 1940 (Barnes, 1940a, p. 495).

The first australite recorded was picked up by Sir Thomas Mitchell on the sandy plains between the Darling and Murray Rivers, New South Wales. It was given to Charles Darwin for identification and description, when he was visiting Australia during the voyages of H.M.S. Beagle (1832–1836).

Professor Gregory and H. J. Grayson collected many australites during explorations in Central Australia. E. J. Dunn's collection of 120 more or less complete australites representing most shapes, was exhibited on loan in the Pavilion of the Mineral Gallery, British Museum of Natural History (Prior, 1927), and later presented to the British Museum by the Misses Dunn. 280 specimens of australites collected by Dr. C. Thorp mainly from Western Australia are also housed in the British Museum. Most Australian Museums

(public and university) have fairly representative collections of the various australite shape groups, and many specimens are in private collections. The largest collection of australites, comprising some 18,000 specimens, is lodged in the South Australian Museum in Adelaide. Other large collections are over 1,000 specimens in the Melbourne University Geological Collection and nearly 1,500 in the author's private collection.

The initial discovery of tektites at any one centre in the various zones of distribution upon the earth's surface, is entirely fortuitous. In certain centres, tektites have been obtained from prospectors, from aborigines and from miners. Because of their keen sense of vision, the aborigines were encouraged to collect australites by stock station owners in Australia. Many australites, too small to be readily distinguished on the ground by the eyes of the white man, were found by natives close to and upon clay pans (Fenner, 1934, p. 65). In 1920, Mr. G. F. Dodwell, Government Astronomer of South Australia, collected 86 australites over an area of one square mile on the thin soil or on the bare limestone characterising the area around Deakin on the Nullarbor Plain (Fenner, 1934, p. 64).

Regions suitable for organized searches of tektites are somewhat limited. Fewer, in Australia, have been found in well vegetated and mountainous areas than upon clay pans, plains and in worked alluvial sands and gravels which present special facilities for collecting tektites. Experience of tektite collecting in the desert regions of Australia, has shown that the most successful method is to look well ahead on the gibber plains, walking with the back to the sun. Sergeant John W. Kennett practised this method in the Charlotte Waters district, Central Australia. He accompanied the aborigines over the gibber plains in searches for australites, and stated that "it was exasperating when the aborigines would pick them up, while I could not sight one" (Fenner, 1940, p. 307). Some weeks after his initial attempts, Kennett succeeded in differentiating tektites on the ground from small, dark-coloured gibber stones, and at the end of a five-year period spent at Charlotte Waters, he became as keen-eyed as the natives in discovering australites.

In the more temperate regions of Australia, the most successful method of collecting australites, is to search old roads, borrow pits, cliff edges and patches naturally bared of vegetation, during or after rain. Under these conditions, in centres of australite concentration, the tektites are washed clean and become conspicuous amid surrounding materials which include black buckshot gravel, broken glass, beetle cases, scorched resin blobs from plants such as Xanthorrhoea and fragments of charcoal from scrub fires. Areas stripped of their cover of vegetation and soil by erosion or by artificial means are obviously areas best suited for the discovery of tektite glass in tektite sprinkled regions, once they have been rain-washed and wind swept. In recent sand dune areas, as in parts of the Moonta district of South Australia, much sifting of sand has to be accomplished to collect australites.

Tektites are also collected during ploughing or digging operations. Specimens exposed in this way are known from South Gawler and Wasleys in South Australia, from Portland, Corop and Port Campbell in Victoria, and from Liverpool in New South Wales. They were also collected from the cradles of gold washers on the Turon River, New South Wales (Clarke, 1855, p. 403). One such specimen so collected was brought up from a depth of 30 feet below the surface. One at Trentham in Victoria, dug out from below auriferous gravel, was resting on Silurian bedrock. Australites have been collected in considerable quantities during placer mining activities, more

especially from alluvial gold deposits at Mount William in the Grampians, Victoria. Dunn's account (1912a) of seeing a kerosene tin full of australites collected during gold washing operations at Mount William, would indicate a secondary natural concentration by stream action of many thousands of australites. They occurred in wash-dirt that rested on Carboniferous bedrock. The location of this large quantity of australites is now unknown.

Detailed collecting at Port Campbell, Victoria, in a coastal stretch of country half a mile or so wide and ten miles long, has yielded approximately 1,500 australites. The especial value of this collection lies in the fact that the exact location and position of rest of each specimen were noted, and fragments as well as complete or nearly complete forms were all collected to make the assemblage as representative as possible. Few of the fragments fitted one another, and presumably the others each represent a different australite. By noting the positions of rest of these australites on the ground, it was found that over 90 per cent. complete or nearly complete forms lay on the earth's surface with anterior surfaces upwards. This position of rest points to the fact that they turned over on striking the earth, or were subsequently rolled over, because during flight, the anterior surfaces of australites faced towards the earth's surface.

The greatest concentration of australities so far collected on the surface from any one limited patch of ground searched over, occurs near Stanhope's Bay, between Peterborough and Warrnambool, Victoria (Baker, 1956). Here, australites were found at the rate of one per yard. An area of 450 by 200 yards consists of a bared old soil horizon on which rest buckshot gravel, occasional aboriginal flints and some 400 or so australites (complete and fragmented). The collection represented nearly all of the known usual australite shape types. The area was particularly suited to searches for australites, being within the known centres of concentration in the australite strewnfield, and being a rain-washed, wind-swept patch on the landward side of Pleistocene dune limestone rock capping the Miocene cliffs of the district.

In other large collections of australites, e.g., the W.H.C. Shaw collection of 3,920 specimens (Fenner, 1934, p. 62), the John Kennett collection of 7,184 specimens (Fenner, 1940, p. 305), and the F.B. Allen collection of 823 specimens from the Kalgoorlie district of Western Australia (recently donated to the Melbourne University Geological Collection), there is little evidence of similar details having been noted as for the Port Campbell collection. In many collections, specimens are all grouped together as coming from a general locality such as Central Australia, Western Australia, Nullarbor Plain, Western District of Victoria, Long Plain district of north-west Tasmania, &c. — locality names that refer to areas covering many squares miles of territory.

Thousands of australites have been collected over several years by George Aiston at Mulka, Central Australia (Fenner, 1935a, p. 127). In this area, australites have now become scarce. The aborigines collected them in exchange for sweets and money.

The natives were responsible for distributing hundreds of australites among collectors, once they realised that the white man would offer a small reward for them. Both Shaw and Kennett utilised the aborigines in building up their large collections (Fenner, 1940, p. 308). Fenner considered that the number of australites collected depended on the ability of searchers for them. The Australian aborigine, with his particularly acute vision, was a valuable asset in such searches.

The numbers of australites in known collections up to 1935, are recorded as 7,353 specimens in museum collections and 4,593 in private collections (Fenner, 1935a, pp. 126-7). An additional 9,500 or more have been added to collections since Fenner's 1935 census of australite numbers. It was estimated that some 20,000 australites have been collected or have come under the notice of interested authorities (Fenner, 1935a, p. 129); this number must now be increased to 30,000-35,000.

Factors affecting the possibilities of collecting australites are the varieties of climate, relief and vegetation presented in the vast area of country over which they are distributed. One to ten millions of australites were estimated by Fenner to have fallen over the Australian continent, and this does not take into account the many thousands more that possibly fell in the neighbouring seas.

The collection of comparatively few tektites from the Sunda Archipelago, northwest of Australia, compared with their abundance on the Australian continent, is due to tropical vegetation and the preponderance of sea within that area (F. P. Mueller, 1915). Larger numbers were only collected in certain areas because of mining operations, as on the Malay Peninsula and the island of Billiton. The first billitonite recorded was found by S. Mueller in 1836 at Pleihari, southeast Borneo. F. P. Mueller (1915) found four tektites near Tutong Station, southeast of Brunei township in 1913. Since then, other specimens have been collected from southwest Borneo.

There is an interesting record that Preuss (1935) " succeeded in proving " that " a much less valuable australite " had been passed off as a billitonite in V. M. Goldschmidt's collection at Heidelberg in Germany, and that " even less valuable moldavites " were occasionally imitated from bottle glass, as shown by an example in the Jena collection. Evidently because billitonites are somewhat harder to come by than either moldavites and australites, Preuss considers them to be more " valuable ", despite the fact that billitonites are by no means as geometrically perfect as australites, and are frequently much more corroded than either australites or moldavites.

It has been estimated that approximately 650,000 tektite specimens have so far been recovered from the eight accepted true tektite strewnfields of the earth. These are apportioned thus: Australites—40,000; Bediasites—2,000; Billitonites and Malaysianites—7,500; Indochinites—40,000; Ivory Coast Tektites—200; Java Tektites—7,000; Moldavites 55,000; Philippine Tektites (Rizalites, &c.)—500,000 (Beyer, 1955b).

CHAPTER II.

TEKTITE TERMINOLOGY.

Many terms have been coined in descriptions of tektites, some in foreign languages having been adopted into English accounts of tektite shape and structure. For purposes of ready reference, alphabetical lists of the shape terms and structure terms are presented herein, with short descriptions.

SHAPE TERMS.

The shapes of tektites are variable. Many resemble commonplace objects in their form or outline. Some are of curious shapes difficult to assign to any particular stage of tektite development or even to compare with ordinary objects in shape. Most of the terms employed are therefore non-committal and have been intentionally selected as such by the authors concerned, so that no definite origin and no precise geometrical form is implied. Descriptive terms for moldavites are largely due to F. E. Suess (1898, &c.), Stelzner (1893), Kaspar (1938) and others, those for indochinites to Lacroix (1932, &c.), those for rizalites to Beyer (1934, &c.) and Heide (1938), those for bediasites to Barnes (1940), and those for australites to Fenner (1934, 1938, 1940).

Aberrants—rare forms including "aerial bombs", "coins", "peanuts", "pine-seeds", "crinkly-tops", "elytra-shaped" forms and others of unusual shape. The term is used more usually in references to certain australites.

Aerial-bombs or Air-bombs—flow-lined australites shaped like bombs.

Batons—cudgel-shaped indochinites.

Beans or kidneys—flat specimens, probably related to oval australites.

Boats—more elongated oval-shaped australites with the short diameter less than half the longer diameter, and sides more or less parallel (Plate V, fig. F).

Bowls—rare, small forms of australites 7·5 to 9 mm. long, 4 to 5 mm. wide and 3 mm. deep. Shaped like round and elongated bowls and thin-walled, never more than 0·5 to 1 mm. thick.

Bungs—larger australites of core-like character, formed by flaking away of portions of anterior surfaces and equatorial regions of modified originally spherical forms (Fenner, 1938b, p. 204).

Buttons—australites with a central, usually dome-shaped portion known as the core or body portion, surrounded by a relatively flat ring of glass constituting a flange. The flange is formed in the equatorial regions of the body portion and is usually narrow in comparison with the diameter of the core (Plate XV). Buttons have also been referred to as saucer-shaped tektites. Suess (1909) likened them to short mushrooms. Apart from australites, only one other tektite—from the Philippine Islands—has been regarded as having a button-shape (Heide, 1938).

Canoes—boat-like australites with narrow pointed ends frequently turned backwards. Some better preserved examples have a narrow imperfect flange, but more often a small, sharply defined equatorial rim.

Cores—the ultimate shapes of any australites reduced in size by natural flaking from the peripheries. A pronounced flaked zone around the equator of any such australite, is produced by the action of terrestrial or atmospherical agencies, either upon the earth's surface or during supersonic flight through

the air (Baker, 1940, p. 492 and 1955). Cores are round (Plate XV, fig. 3) or elongated (Plate I) according to the original shape of the primary form. Some cores are referred to as "bungs", some have been likened to the shape of a "scoop of ice-cream" (Buddhue, 1941), Small, more or less rounded javaites are regarded as the cores of complete forms after abrasion of the "flange" and strained "cracklin" (Heide, 1939). Cores of moldavites, referred to as "nuclears" by F. E. Suess (1900), have polygonal and irregular outlines.

Crinkly-tops—boat, lens or sometimes teardrop or dumb-bell-shaped australites where glass from the anterior surface, instead of building up into a flange, has spread out over the perimeter of the posterior surface, leaving a series of ridges likened to the edges of a pudding cloth that does not cover the whole pudding (Fenner, 1934, p. 69 and 1940, p. 312).

Discs—thin, flat australites, almost circular in outline, with the flange broad in comparison to the diameter of the central core. Some varieties are elliptical in outline and plate-like (Plate V, fig. E).

Discoidal forms—circular and elliptical, disc-shaped forms of moldavites and some other varieties of tektites, which are much thicker than the disc-shaped australites, and are not flanged.

Dumb-bells—elongated australites with a constriction (waist) in the middle portions (Plates IX and XV). The waist has been compared by F. E. Suess (1909) with the constriction of an hour-glass. Dumb-bell-shaped specimens also occur among the indochinites and rizalites.

Elongated forms—tektites with one diameter longer than the other and longer than the vertical axis usually. Include oval, boat, dumb-bell, canoe and teardrop-shaped australites (Plate XV) and elongated australite cores, also ellipsoidal billitonites (Plate I, figs. D and E), indochinites (Plate VI), Ivory Coast tektites, some Philippine Islands tektites (Plate XIX) and the "pine-cone"-shaped forms among the moldavites (Plate III, figs. 3a to 3d).

Fladen—pancake-shaped moldavites from Bohemia.

Flat trays—small and of varied type, approaching helmet-shaped forms on the one hand, flat discs on the other hand, among australites.

Helmets—bowl or cup-shaped australites with broad flange curved back as an entity from a small, insignificant core portion. Comparable types with oval-shaped outlines occur among the moldavites (F. E. Suess, 1909).

Hollow tektites—rare, relatively thin-walled, bubble-like australites (Plate XIV), Philippine tektites and indomalaysianites (Plate XIV). Represented by broken fragments ("egg-shell-like") among several of the tektite groups.

Indicators—australites subjected to equatorial chipping and flaking (fig. 37), but still retaining portion of the margin that generally "indicates" the original form prior to flaking. Often lens-shaped, but a few retain evidence of the former presence of a flange and were thus derived from button-shaped australites. Some indicators were produced by flaking away of the equatorial regions of oval and boat-shaped australites.

Ladles—aberrant dumb-bell-shaped australites with one end typically larger than the other, and the narrower end turned upwards.

Lenses—biconvex, lenticular australites (Plate XV) resembling the cores of button-shaped forms with flanges removed. Sometimes called lensoids. Few lenses are recorded among other tektite groups.

Nondescripts—fragments of australites that cannot be precisely classified with any particular shape type.

Obsidian buttons—button-shaped australites.

Obsidian bombs—all shape types of australites.

Obsidianites—an old term for various groups of the tektites, and like the terms "obsidian buttons" and "obsidian bombs" has fallen into disuse.

Ovals—like buttons or lenses, but with a shorter diameter equal to one half or three-quarters the longer diameter. Differentiated into broad and narrow ovals. Flanged forms infrequent. Most common among australites, but one example recorded from Java (Heide, 1939).

Pine-seed forms—small australites, elliptical in outline, flat above (i.e. posterior surface), convex below (i.e. anterior surface) and tapering at the edge to a thin flange (Plate V, fig. D). Flange flat at the extremities of the specimens, but curved back on the middle part of the upper (i.e. posterior) surface (Skeats, 1915b, p. 363).

Pitted discs—flat, disc-shaped australites with bubble pits of abnormal dimensions for the size of the specimens, on both flange and core. Said to be formed by erosion and abrasion of lens-shaped forms (Fenner, 1934, p. 69), but are more likely independent forms developed as such during atmospherical flight.

Plaques—plate-like indochinites.

Potsherds—fragmented moldavites resembling pieces of broken pots.

Primary forms—sphere, spheroid, apioid and dumb-bell shapes, all of which, except the sphere, are possible figures of revolution, and evidently represent the primitive shapes assumed by australites when initiated as separate entities in an extra-terrestrial environment.

Round forms—approximately circular in plan aspect, such as disc, button and lens-shaped australites.

Secondary forms—modifications of primary forms, australites in particular, that developed flanges or rims by backward flowage of glass melted from the front polar regions during supersonic flight. Buttons, lenses, ovals, boats, dumb-bells, canoes and teardrops result from this process, also aberrant forms. Modifications resulting from ablation and/or fusion stripping of material from the equatorial regions of australites, result in the secondary forms such as some of the cores ("bungs").

Spalls—a term applied more especially to fragments of bediasites having one surface usually concave (Plate VII).

Spheres—more or less round in all aspects and sometimes called spheroids. Such ball-shaped objects occur among javaites, rizalites, Colombian (?)tektites, Ivory Coast tektites, malaysianites and moldavites, but are seldom encountered among australites unless accidentally produced by weathering. Referred to as balls, burrs and drops among moldavites (Kaspar, 1938), and as balls or drops among javaites (Heide, 1939).

Spoons—large australites, ladle-like in shape and similar to the spoon-shaped moldavites.

Teardrops and *pear-shaped forms*—stopper-shaped bodies, sometimes with relatively slender tails. Regarded as the ultimate separate halves of dumb-bell-shaped tektites (fig. 30), especially australites (Fenner, 1940, p. 314). Some show flattening, others the tendency to develop flanges, although these are mainly broken by erosion because of their fragile character. Pear-shaped forms occur among the indochinites (Plate VI).

"Trilobites"—fragments of elongated australites with "saw-cuts". After erosion along the "saw-cuts" and breaking away of the requisite portions, the objects simulate certain trilobites with genal spines.

The various shape terms used in descriptions of the several tektite groups so far discovered upon the earth's surface are summarised in Table 1.

TABLE 1.

Showing recorded shapes among the various tektite groups.

Shape Term.	Australites.	Bediasites.	Billitonites.	Indochinites (and malaysianites).	Ivory Coast Tektites.	Javaites.	Moldavites.	Rizalites.
"Aberrants" ..	+	—	—	—	—	—	—	—
"Batons" ("Cudgels")	—	—	—	+	—	—	—	—
Boats	+	—	—	—	—	—	—	—
Bowls ("Helmets") ..	+	—	—	—	—	—	+	—
Buttons	+	—	—	—	—	—	—	—
Canoes	+	—	—	—	—	—	—	—
Cores ("Bungs") ..	+	—	—	—	—	+	+	—
Cylindrical forms ..	—	—	+	—	—	—	+	+
Discs and Plates ..	+	—	—	—	—	—	+	—
Discoidal and plate-like forms (not flanged)	—	—	—	+	—	+	+	+
Dumb-bells	+	—	—	+	—	—	—	—
Ellipsoidal forms ..	+	—	+	+	+	—	+	+
Fladen	—	—	—	—	—	—	+	—
"Gherkins" ..	—	—	—	+	—	—	—	—
"Gum-drops" ..	—	+	—	—	—	—	—	—
Hollow forms ..	r	—	—	+	—	—	r	r
"Indicators" ..	+	—	—	—	—	—	—	—
Irregular forms ..	—	+	+	+	+	+	+	+
Lenses	+	r	—	—	—	—	—	—
Ovals	+	—	—	—	—	r	—	—
Pine-cone-shaped ..	—	—	—	—	—	—	+	—
Pine-seed-shaped ..	r	—	—	—	—	—	—	—
Plaques	—	—	—	+	—	—	—	—
Potsherds	—	—	—	—	—	—	+	—
Spalls	—	+	—	—	—	—	—	—
Spheres and spheroids	r	+	+	+	+	+	+	+
Tabular forms ..	—	+	—	—	—	—	—	—
Teardrops and pear-shaped forms, stopper-shaped, and aerial bombs	+	r	r	+	—	—	+	r

Key : + = present ; — = not recorded ; r = rare forms.

These shape terms are derived from the works of Fenner and Dunn (australites), Baker (australites), Barnes (bediasites), Van Dijk (billitonites), Lacroix (indochinites, and Ivory Coast tektites), Heide (javaites), Suess, Stelzner, Berwerth, Kaspar (moldavites) and Beyer, Heide, Winderlich (rizalites).

Shapes recorded for the doubted South American tektites are:

Colombian (?)tektites—balls or spheres, some flattened on one side. Others ellipsoidal, discoidal, fusiform or irregular.

Peruvian (?)tektites—from Macusani—rounded pieces, from Paucartambo—sub-spherical.

Although some of the terminology for the different shapes encountered among the various groups of the tektites, is similar, this arises from the limits placed upon shape description by the relatively small number of available terms that can reasonably be applied to tektites, without of necessity indicating their origin, which still remains unproven. Moreover, the similar terms are sometimes used rather differently by different authors, so that terms common to the separate tektite groups, do not always refer to identical shapes from group to group. For example, the term "spheres or spheroids" is common to all the tektite groups, and it is seldom stated whether such forms are primary and well preserved, whether they are secondary modifications of the primary forms brought about by their rapid transit through the earth's atmosphere, or whether they have resulted from the weathering and abrasion of either primary or secondary forms subsequent to their arrival upon the earth.

An examination of the various names employed for the shape types represented in each tektite group, reveals that there are quite marked variations among the shapes from group to group. Of all these groups, it is evident that the australites comprise the group with the greatest array of different shapes, and that the complete or nearly complete forms represented, are so far unmatched among all the tektite strewnfields of the world, for their almost perfect geometrical symmetry, regularity of outline and associated features, and in their possession of flanges.

STRUCTURE TERMS.

Include external features and internal structures of tektites.

Ablated tektites—forms indicating surface wastage by melting and evaporation during the atmospheric phase of supersonic flight.

Anterior surface—the smoother, hemispherical surface of an australite, with concentric or spiral flow ridges and fine, radial flow lines (Plates VIII, fig. C and IX, figs. A and D). This surface faced earthwards during atmospherical flight, and was subjected to superficial sheet fusion.

Bubble cavities—large internal bubbles with smooth walls, frequent in fragmented tektites, sometimes transected in sliced specimens (fig. 8C). Gas content low and evidently under negative pressures.

Bubble craters—large surface depressions wider and deeper than bubble pits (Plate I, fig. F).

Bubble pits—minor depressions formed by the bursting or collapse of small gas bubbles on escape. Common on all tektite varieties that are not excessively worn. Some smaller pits are probably etch pits where more siliceous material has been removed. Occur principally on the rear surfaces of australites (fig. 8C), where sometimes referred to as "cells" (Stephens, 1897) and noted as extending over the flange and "central nucleus" of some specimens, but invariably rare thereon, and never common on anterior surfaces.

Bubble tracks—grooves and flutings on flaked equatorial zones (Plate I, fig. H) and on unflaked anterior surfaces of some australites. Resemble channels on billitonites and some other tektites, and regarded as bubble tracks because most are chain-like arrangements of coalesced gas bubbles, often with vermicular,

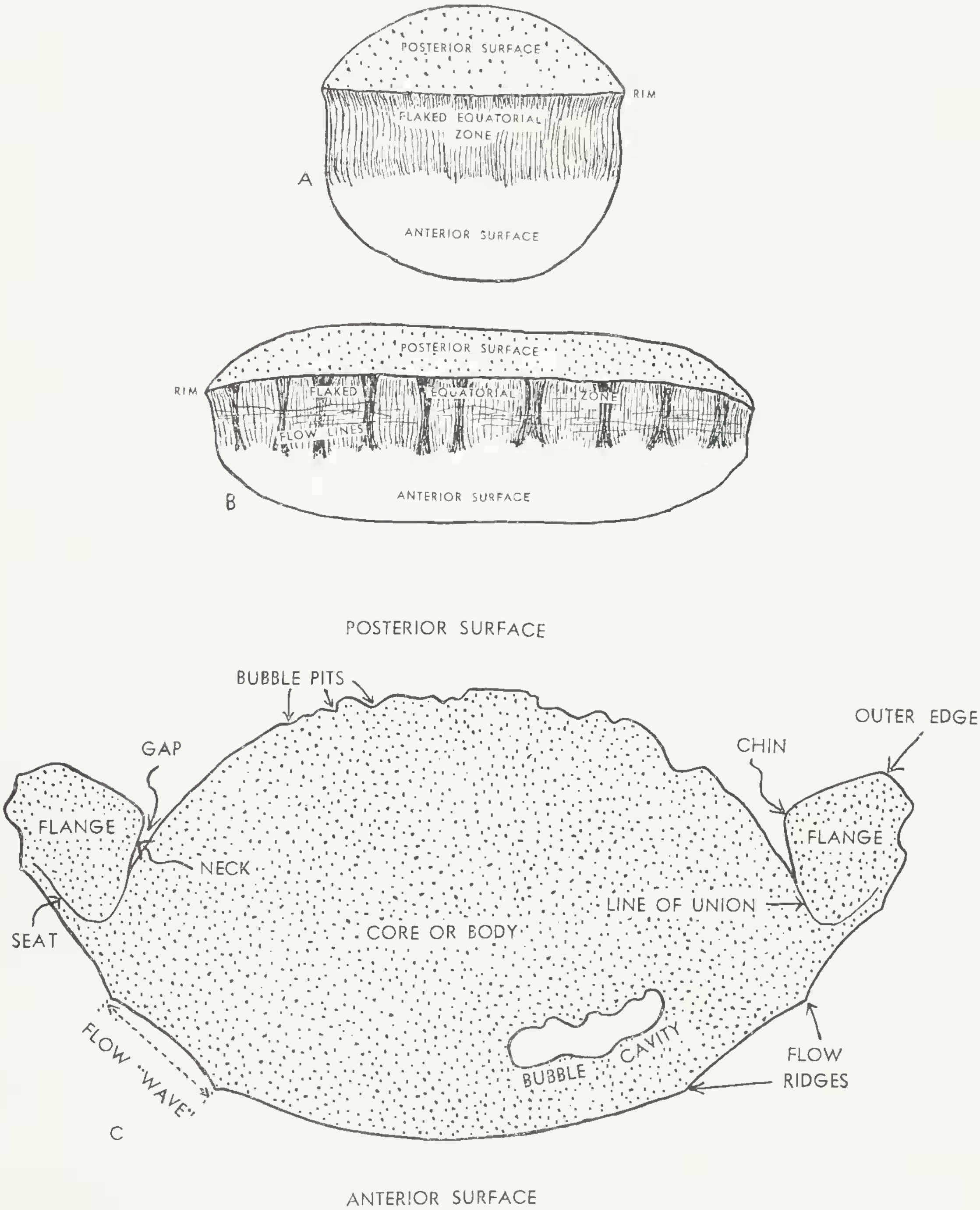

FIGURE 8.—Australite nomenclature.

A—round form with flaked equatorial zone recurving towards rim at junction with posterior surface.

B—boat-shaped core form; darker shading represents ridges separating slightly concave areas.

C—section through button-shaped form.

(A and B reproduced from Min. Mag. XXV, 1940; C—after Baker, 1944.)

segmented character. Sometimes they are long, deep bubble pits drawn out in flow directions (Plate II, fig. 8), especially on the tails of teardrop-shaped forms, and sometimes they are much accentuated by natural etching along flow line directions.

Cannelures—deep or shallow grooves on drawn-out indochinites (Plate VI), and evidently comparable with " bubble tracks."

Chin—the rounded inner edge of flanges on australites (Dunn, 1912b, p. 12) as shown in figure 8C.

Cracklin (" *krakelé* ")—fine, irregular cracks on anterior surfaces of certain Javanese tektites, comparable with the cracklin (fine reticulating cracks) of chinaware.

Cupules—cup-shaped pits on the outer surfaces of indochinites and Ivory Coast tektites, and comparable with the bubble pits of other tektites (Plate XVIII, figs. 9 and 10).

Equatorial zone—the margin of any round or elongated australite. Sometimes occupied by a narrow projection or rim, sometimes by a broader band or flange, occasionally by a partially or completely continuous flaked region around the circumference of larger cores (figs. 8A and B, and Plate X, fig. A). Divides pitted posterior surfaces from smoother, flow-ridged anterior surfaces.

Fiederung—fine striations (" schlieren ") within and normal to the trend of deeper grooves in moldavites.

Flange—a projecting annular band of tektite glass built up in the equatorial regions of some australites and separating posterior from anterior surfaces. Likened to " planetary rings " and called " rims " by some authors, " lips " by others. Of extreme rarity and by no means as perfect in other tektites.

Flow grooves—gutter-like depressions sometimes called " furrows " or " open channels " and hence broader and deeper than flow lines. Likened to " worm tracks " (Beyer, 1935) and " U-shaped crevasses " (Hodge Smith, 1932, p. 582), and called " bubble tracks " (Baker, 1940a, p. 488). They occur on billitonites (Plate I), Busuanga (Philippines) tektites, some australites (Plate X, fig. A), bediasites (Plate VII), and indochinites (Plate II), but are perhaps most characteristic of the billitonites.

Flow lines—streaks (" schlieren ") on external surfaces (Plate II, figs. 1 to 5) and within tektites (Plates X, fig. B, XI and XII). Frequently associated with areas showing strain polarisation and differences of refractive index. Represent directions of gas streaming, directions of elongation of partially resorbed lechatelierite particles and directions of movement of glass layers varying slightly in chemical composition.

Flow pattern—embraces simple and complex, external and internal flow structures compounded of flow lines, strain lines and flow grooves.

" Flow " ridges—concentrically or spirally arranged, ridge-like elevations, often with sharp crests, developed more especially upon the anterior surfaces of australites (fig. 8C). Often wavy (Plate VIII) and crinkled (Plate IX, figs. A and B) towards the equatorial edge of anterior surfaces of flanges.

"Flow" waves—trough structures on anterior surfaces of australites (fig. 8C). Evidently produced during skin friction and some ablation in the expansion zones behind shock wavelets during turbulent boundary layer flow in the medium (air) traversed. The "flow" ridges would be residuals to which shock wavelets were attached, (cf. fig. 36).

Gap—the area between the posterior surface of the body portion and the overhanging neck surface of flanges on australites (fig. 8C). The gap regions of australites are frequently infilled with soil, sand (Plate IX, fig. C) or clay when collected. The infilling materials are invariably akin to the surface materials on which the tektites rested, or within which they were entombed.

Gibbosity—bulbous portion of a dumb-bell or a teardrop-shaped form.

Gouffrierung—minute feathery groovings ("brush-marks") invisible to the naked eye. Occur on moldavites along the general trends of coarser groovings. Also observed as fine flow lines on australites and indochinites.

Gouttières—vermiform and annular grooves or "gutters" on indochinites.

Höfchen—flow grooves forming a circular depression around an elevated central portion ("island" or "tischchen") of tektite glass. Characteristic of billitonites (Plate I, figs. C and D), rare on other tektites.

Lechatelierite particles—microscopic bodies of widely variant shape (figs. 22 and 23) usually aligned in the flow structures of tektites and representing quartz or other non-hydrous silica particles after which they are pseudomorphous.

Line of union—the line of contact between flange and body portion as seen in cross sections of australites and in naturally etched, broken specimens (fig. 8C).

Lunar craters—U-shaped, circular grooves surrounding small knobs of tektite glass (cf. "tischchen" and "höfchen"). Thought by most authors to represent areas of strong etching along certain flow directions.

Navels—peculiar structures more common on billitonites (Escher, 1925, p. 157) and analogous with "tischchen" and "höfchen".

Neck—the surface of an australite flange occurring below the chin region. It faces and usually overhangs the equatorial periphery of the posterior surface of the central body portion of australites, and the trend of its exposed surface is contiguous with that of the line of union, (fig. 8C).

Plissures (Plissüren)—wrinkles and streaks on tektite surfaces (Plate XVIII, fig. 5).

Posterior surface—the normally bubble-pitted, occasionally smooth or finely striated, almost hemispherical rear surface of an australite (Plate V). It was directed away from the earth during the atmospherical phase of earthward flight.

Rim—a small projection from the equator of certain tektites (figs. 8A and 8B). Typical of lens-shaped australites, where it separates posterior and anterior surfaces. Rims (and flanges) have been referred to as "circumferential rings" (Thorp, 1914).

Saw-cuts—deep and parallel-sided, straight or curved, crack-like openings in australites, formed later than and often along the flow line structures and most likely representing lines of easiest natural etching.

Saw-marks—shallow "saw-cuts" resembling the impressions made by a hand-saw on gently drawing it across a piece of wood. Represent weathered and abraded remnants of previously more deeply etched grooves.

Schmelzrinnen—"melt grooves" on rizalites (Winderlich, 1948, p. 113).

Seat—a projection of australite glass from the equatorial portion of an anterior surface, up into the base of the flange (fig. 8C). Seen in sectioned specimens (Plate XII, fig. B), sometimes well-marked on fractured, slightly weathered specimens. It is in contact with, but marked off from the rest of the flange by different flow patterns. The flange appears to be "seated" upon this structure, which is continuous around the flanged australites at the junction of core and flange.

Septum—a partially developed, thin wall of tektite glass dividing two sections of a hollow australite with a double bubble cavity. Only one specimen so far recorded (Plate XIV, fig. 2).

Shank—the drawn-out portion ("tail") of a teardrop-shaped form.

Smooth band (*Flange band*)—a band of smooth-surfaced glass (unless much etched naturally) about 2·5 mm. broad, situated around the periphery of the posterior surface of some australites. It represents the position of flange attachment prior to flaking; newly shed flanges leave the flange band with a highly vitreous lustre.

Swirls—circular to elliptical flow-lined areas on the normally bubble-pitted posterior surfaces of australites (Plate V, figs. B and C), which possibly represent patches of more vitreous glass relatively free of bursting bubbles at the time of formation of the primary surface.

Tischchen—the elevated central portion ("island", "knob" or "little table") in navel structures, which is surrounded by a circular groove ("höfchen"), and the height of which is on the same level as the tektite glass surrounding the structure.

Waist—the constricted middle portion of the elongated dumb-bell-shaped tektites (Plate XV, fig. 5).

THE CLASSIFICATION OF TEKTITES.

Apart from classification into major groups according to their location upon the earth's surface, most tektite occurrences have been further subdivided according to certain characteristic features they possess. Most classifications have been based on shape variations, some on chemical variations, and a few on physical variations other than shape. Thus Dunn (1908a) first drew up a classification of australites according to shape and size and Fenner (1934, p. 67) presented a more elaborate classification which was devised as a working basis for the description of large collections such as the W.H.C. Shaw collection of nearly 4,000 specimens. Minor additions and modifications have been made to Fenner's (1934) classification as further collections became available for study (Baker, 1937 and 1940b, p. 312, and Fenner, 1940, p. 315). Beyer (1934) classified the large group of the Austro-Indomalaysian tektites into four groups called *physical types*, by combining certain shapes and structures as they are encountered in various geographical settings. The moldavites of Bohemia and Moravia were subdivided according to shape into four main groups (F.E. Suess, 1900), while the indochinites were subdivided on the basis of shape relationships

and on certain structures referred to as "deformations" (Lacroix, 1932) into primary forms and secondary forms, the first group consisting of the several shape types encountered, and the second composed of "traumatisms" or deformations of mechanical origin, and "corrosions" or deformations of chemical origin.

The various shape types so far recorded for the various tektite groups found in the several strewnfields upon the earth's surface are listed in table 1 for comparative purposes. More detailed groupings can be obtained by reference to the works of authors who have classified tektites according to their shape types.

Chapter III.

THE NATURE OF TEKTITE GLASS.

Including colour, optical properties, weight, specific gravity, hardness and behaviour to heat treatment.

Tektites are brittle and they break with a conchoidal fracture having rippled surfaces, but sometimes they crack along flow directions. From the chemical aspect, Lacroix (1932) thought that tektites formed a very homogeneous series, although detailed examination of the Far Eastern tektites revealed they were chemically and physically slightly heterogeneous. Merrill (1911) regarded all tektites as consisting wholly of amorphous glass, without any traces of trichites, while van der Veen (1919) showed that billitonites furnished the powder spectrum of an amorphous material. The powder spectrum of indochinites was also shown to be that of an amorphous substance by M. Wyart (see Lacroix, 1932).

Tested for magnetic properties by M. Chevalier, tektites gave negative results (Lacroix, 1932), while ultra-violet ray examination revealed no trace of fluorescence in the Far Eastern, Czechoslovakian and Australian tektites. The same applies to all the other groups of tekitics.

COLOUR, LUSTRE, ETC.

When sufficiently thick, most tektites are jet-black in reflected light, but the colour varies in transmitted light with the different types. Tektites generally have a dull lustre on natural surfaces, due to atmospherical weathering, but freshly fractured surfaces reveal a brilliant vitreous lustre.

The colour of moldavites is perhaps the most outstanding among the different types of tektites. Those from Budweis in Bohemia are bottle-green in transmitted light (Mayer, 1788), while most others are distinctly brownish-green. Comparisons of tektite glass from Bohemia, the Dutch East Indies and Australia by Suess (1909), showed that all are jet-black in reflected light, but when held against the light, the moldavites revealed pure green and brilliant tints, even large lumps being clear and transparent. Brownish and less transparent tints predominate in billitonites, australites and other tektites, which are largely clear and transparent only on the thin edges of specimens and in thin sections. The colour differences are ascribed to the presence of ferrous or ferric oxides respectively. As early as 1881, Makowsky (pp. 21 and 26) stressed the absence of microlites from moldavite glass.

Australite glass, when sufficiently thin, is seen to be colourless to pale yellowish-green, free from crystalline inclusions. It is transparent, isotropic except for weak strain birefringence along lines of union or in areas of contorted flow. Occasional more deeply coloured areas in australite flanges are parallel to secondary flow banding (cf. Twelvetrees and Petterd, 1897; Mahony in Dunn, 1908; Thorp, 1914; Skeats, 1915b, p. 362; Dunn, 1912b, Plates 10 to 17; Barnes, 1940; Baker, 1944, Plates I and II). The polarisation colours in weakly strained areas are low order grays, while undulose extinction is frequent. The strained bands are much more pronounced under crossed nicols when a sensitive tint plate is inserted. Optical figures in the broader of the strain bands are always too indistinct for accurate determination, but sometimes appear biaxial. The strained areas generally comprise paler coloured bands that are delineated from the more normally pale yellowish-green, non-strained glass.

The Philippine Islands tektite glass is jet-black by reflected light and olive-brown in transmitted light (Hodge-Smith, 1932, p. 583). Twelve Philippine Islands tektites described by Heide (1938) are given as black in colour but without the varnish-like lustre of some billitonites, thin splinters of the glass being dark brown and translucent. The varnish-like lustre referred to by Heide, is often a result of natural etching, which causes many tektites to appear much fresher compared to others that have been subjected only to abrasion and thus dulled.

Thin sections of the Philippine tektites are completely isotropic (Hodge-Smith, 1932, p. 583) and show no evidence of crystallisation or structure. Hodge-Smith did not note internal gas bubbles in the specimens he investigated, but rare, circular gas bubbles have been noted in other specimens (Heide, 1938) and also occasional birefringent streaks produced by strain.

Ivory Coast tektites, Africa, consist of black glass that appears brownish in sufficiently thin splinters (Lacroix, 1934b).

Malayan tektites are jet-black with a finely sculptured, glossy surface (Scrivenor, 1931).

Java tektites are brown coloured and transparent in thin sections and thick plates (Heide, 1939), but are not entirely homogeneous as evidenced by the presence of elongated streaks parallel to wrinkles ("plissüren") on the surface. These streaks ("schlieren") vary in intensity of colour, refractive index and double refraction, due to strain in portions of the glass. No included crystals occur in the javaites, and the only inclusions are rare, small bubbles.

Bediasites are also jet-black in colour, and like the australites and a few examples of the other tektite groups, they have been shown (Barnes, 1940a) to contain flow streaks, included bubbles and lechatelierite particles, besides revealing strain polarisation along the directions of the flow streaks. Indochinites also show these characteristics.

The colour of tektites results largely from the combined absorptions of iron, nickel, chromium and manganese oxides. Both the spectral high visible absorption and the high ultraviolet absorption are due to the high iron oxide content of the tektite glasses, which also gives rise primarily to reduced transmission in the near infra-red. The nature of the colour of tektites and their general transmissive properties, indicate that the reduction of the iron has been retarded. Taken in conjunction with the fact that tektites possess complicated flow-line patterns pointing to a certain degree of inhomogeneity, and sometimes also show variations in optical density, the assumption is that these facts and the possible retarded reduction of iron, indicate that tektites were produced under conditions where time was insufficient for the attainment of a state of equilibrium (Stair, 1955, pp. 49-50).

Among the glass objects doubtfully referred to as tektites, the Colombian glass spheres are dense black in reflected light, but smoky-gray in thin sections, those from Cali have a violet tint (Döring and Stutzer, 1928; Codazzi, 1929). The glass comprising these spheres is isotropic, but with certain refractive index variations. It has a shagreen appearance and is usually free of inclusions, although some darker coloured splinters contain microlites and minute bubbles along flow directions (Döring and Stutzer, 1928). The glass of the Paucartambo occurrence, Peru, is largely isotropic in itself, but contains crystals (Plate XIII) of various minerals (Linck, 1926a, pp. 160-166) around the larger of which are weakly birefringent areas that are sometimes biaxial,

and are regarded as regions where the crystals exerted a dragging effect. The glass from Macusani, Peru, is transparent to cloudy, light brownish-green in colour (Heide, 1936), and is likewise said to contain mineral inclusions.

REFRACTIVE INDICES OF TEKTITES.

Refractive index determinations of moldavite glass by the method of minimum deviation, and comparison of the results (Table 2) with the refractive index values for artificial green glass, show that moldavites have much the lower R. I. (Schwantke, 1909), and are hence not artificial products.

TABLE 2.

n.	Moldavite Glass.		Artificial Green Glass.	
Red	1·475	1·482	1·661	1·659
Yellow	1·494	1·490	1·672	1·672
Green	1·501	1·494	1·687	1·685
Violet	1·514	1·502	1·699	1·696

From determinations of the refringence of moldavites for wave lengths corresponding to lithium, sodium and thallium light on an Abbé refractometer, and the density of a large number of moldavites, it was formerly concluded (Jezek, 1910) that glasses with R.I. = 1·50 and a density of over 2·40 were artificial. Reference to the ranges in refractive index and specific gravity values of the various determinations set out in Table 3, however, reveal values for tektites that occur both above and below the limiting values given by Jezek.

In moldavites, there is an increase of dispersion with temperature increase, from 1·4853 at 170°C. to 1·4931 at 600°C., using helium red. No optical relationship occurs between moldavite glass and obsidian or silica (Rinne, 1914).

The specific refractivity of moldavites has been calculated from the relationship $k = \frac{n-1}{d}$, where k is a constant, n = the refractive index and d = the density of moldavites (Tilley, 1922, p. 277). For this purpose, Tilley used Jezek's R.I. values and five others determined on moldavites in the Cambridge University Mineral Collection. Their range in density was 2·303 to 2·367, range in refractivity 1·4798 to 1·4961, and range in calculated specific refractivity 0·2072 to 0·2122 (average = 0·2089). Graphs of the relationships between density, refractivity and chemical composition for tektites and various natural glasses (Tilley, 1922, pp. 282-3) showed that moldavites occupied a field distinct from rhyolite—obsidians, and were characterised by a higher specific refractivity. From refringence and density studies, Tilley (1922, p. 284) therefore concluded that Jezek's view, which was also supported by Michel (1913), could not be maintained that moldavites were inseparable from rhyolite—obsidians. The specific refractivities and densities of tektite glasses, amply confirm their divergence from terrestrial glasses, and these abnormalities, together with associated evidence, point to the ultimate meteoritic origin of tektites.

The specific refractivity of australites (four specimens) has been determined as ranging from 0·2088 to 0·2128 (average = 0·2109) for densities ranging from 2·386 to 2·453 and n_{Na} ranging from 1·4981 to 1·520 (Tilley, 1922, p. 278). Recent determinations on two specimens from Harrow (Baker, 1955b), are in accord with Tilley's results, the densities ranging from 2·431 to 2·446, $_{Na}$ ranging from 1·512 to 1·517, with the calculated specific refractivity values ranging from 0·2103 to 0·2114 (average = 0·2109).

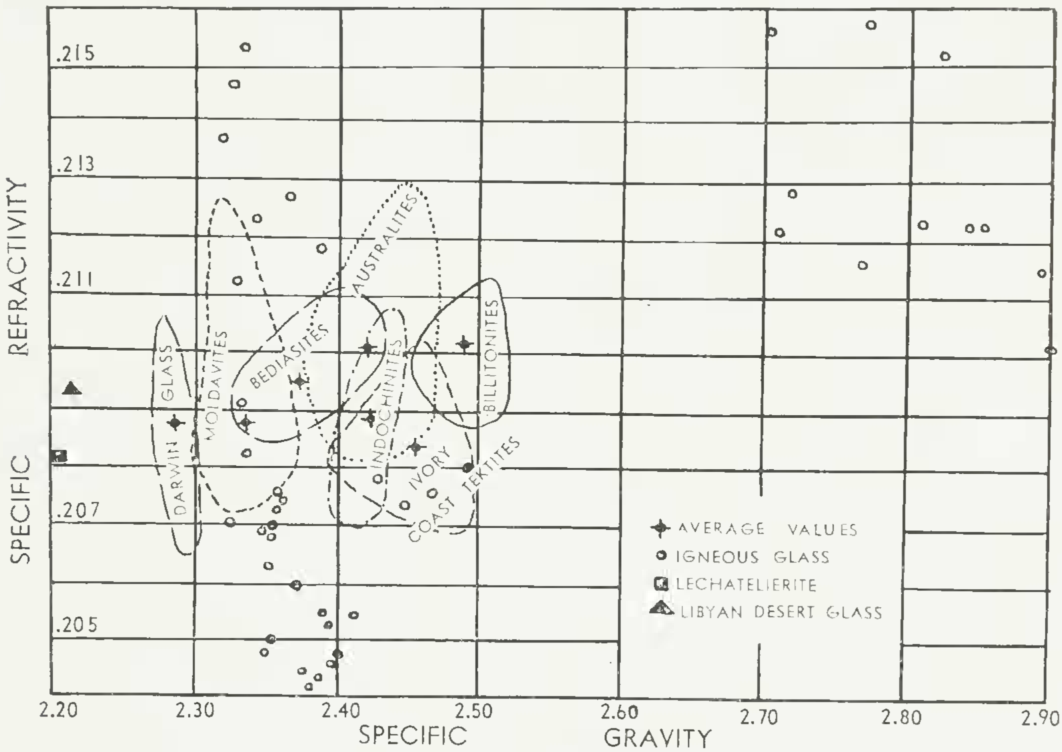

FIGURE 9.—Specific refractivity—specific gravity relationships of tektites (after Barnes, 1940a).

The specific refractivity of the Paucartambo so-called tektite, determined as 0·2058, is lower than that for moldavites and australites (Linck, 1926a, p. 158).

In attempts to establish a theory of tektite origin from volcanic explosions on the moon, the *albedo** and *polarisation angles* of tektites and the moon respectively, have been determined (Linck, 1928, p. 234). Utilizing the Paucartambo so-called tektite, it has been found that the critical angle (polarisation angle) of the Peruvian glass is 33°56′ to 33°31′, that for the moon according to Landerer being 33°17′. The refractive indices are 1·4855 to 1·5097 for the Paucartambo glass, 1·516 to 1·530 for the moon. The albedo of the Paucartambo glass was determined by George Joos as 1 in 0·032, with an error of plus or minus $\frac{1}{4}$ to $\frac{1}{3}$. Wilsing and Scheiner determined the albedo of the moon as 0·029 in its darker portions. Considering that the moon would give an average value for the critical angle, and that the albedo would disconnect it from any state of crystallisation, Linck concluded that these properties showed a satisfactory agreement for tektites and the moon.

* *Albedo* = the brightness of a reflecting surface as measured by the proportion of incident light that it reflects.

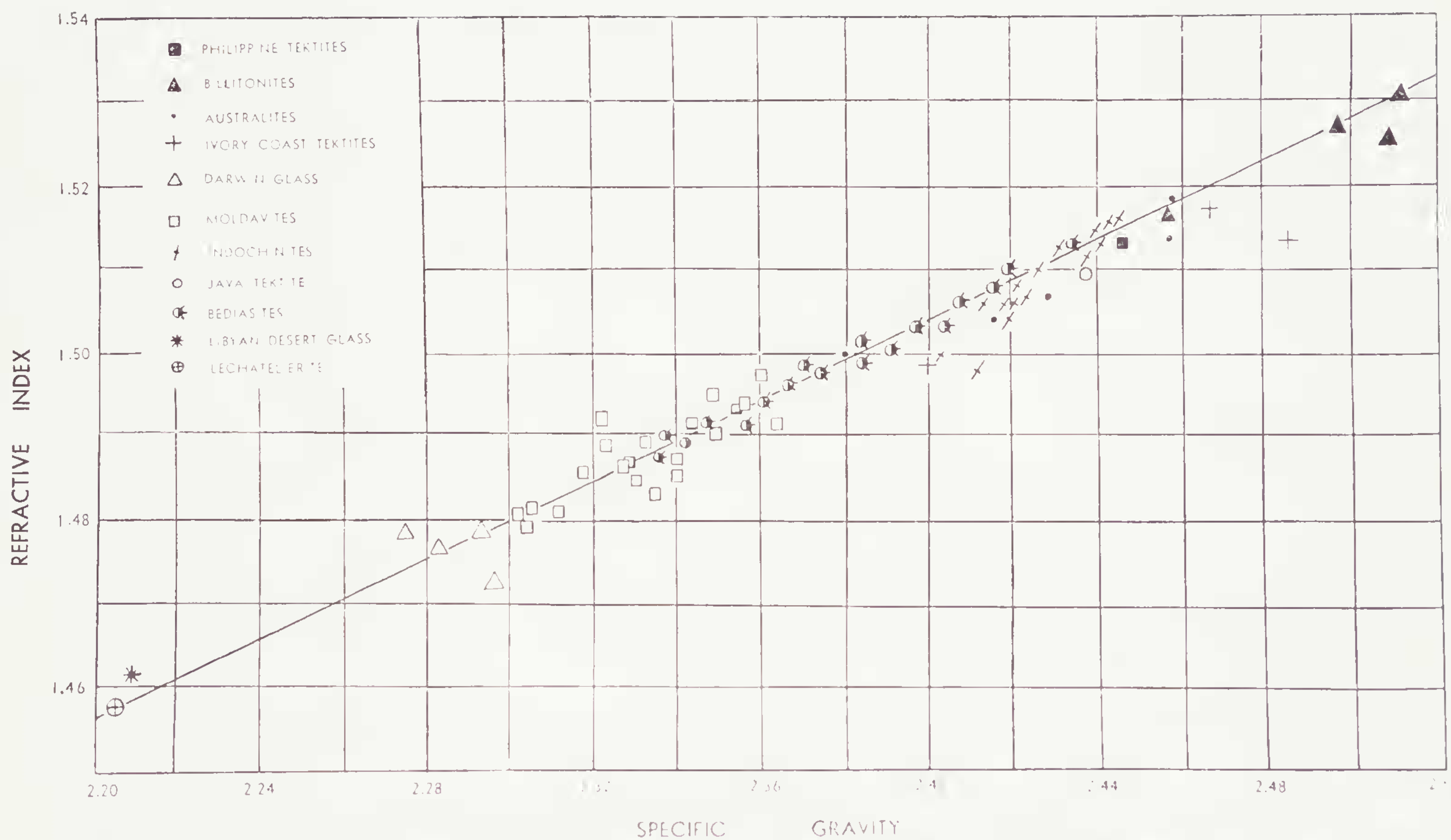

FIGURE 10.—Refractive index—specific gravity relationships of tektites and natural silica glasses (after Barnes, 1940a).

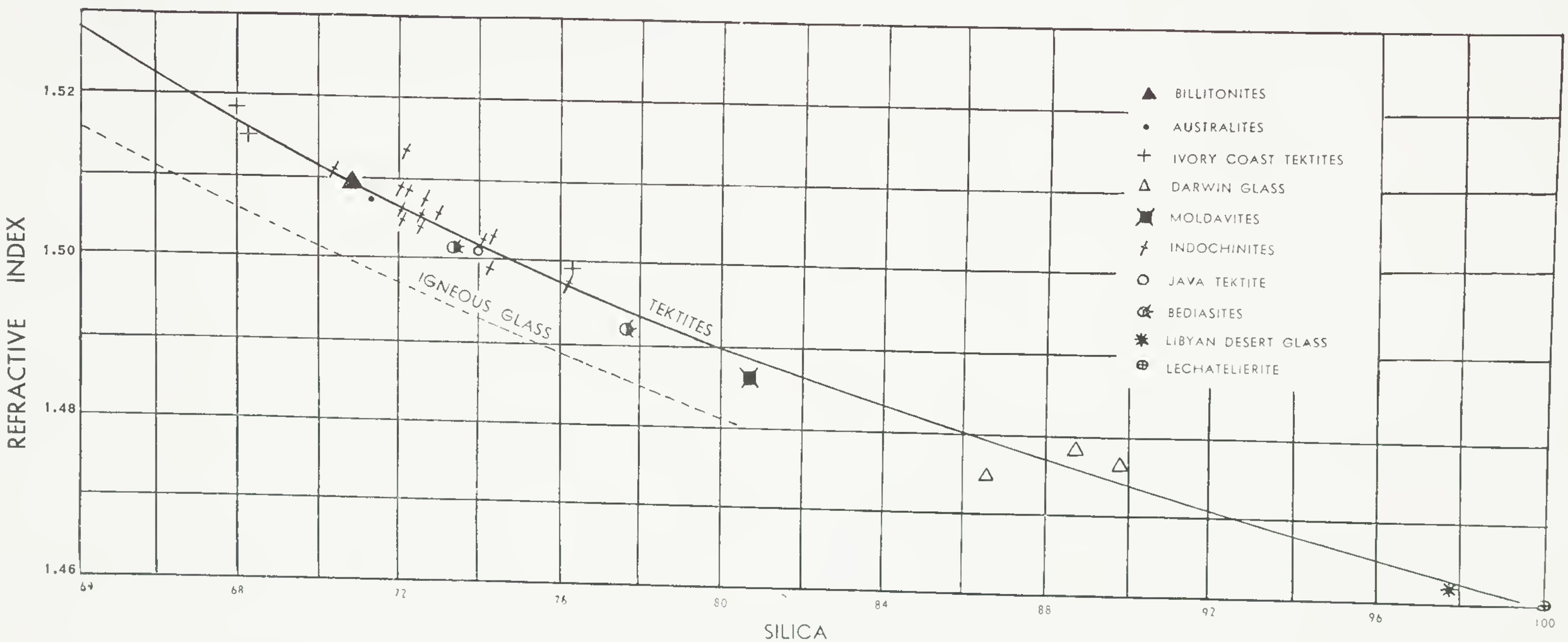

FIGURE 11.—Refractive index—silica relationships for the accepted tektites and silica glass, compared with that for igneous glass (after Barnes, 1940a).

Unfortunately for this conclusion, only the Paucartambo glass was utilized in comparisons with the optical properties of the moon, and since there is still some considerable doubt as to whether the Paucartambo glass really belongs with the group of the true tektites, no conclusions can safely be drawn, and the results of the comparisons must therefore remain in abeyance.

The specific gravity and refractive index values for 36 analysed tektites, many of them due to Lacroix (1929, 1930, 1931, 1932 and 1934) from the Ivory Coast in West Africa, from the Far East, Peru and Czechoslovakia, show uniform decreases from 2·498 to 2·339 in specific gravity and decreases from 1·526 to 1·4867 in refractive index, corresponding with a silica range of from 68·00 per cent. to 80·73 per cent. For these values, the calculated specific refractivities show a uniform increase from 0·2050 to 0·2107. The specific refractivity—specific gravity relationships of tektites and other natural glasses are shown in text figure 9.

The refractive index—specific gravity values for javaites from Solo in Central Java, fit in between the average values for australites and indochinites (Heide, 1939), and there is a marked overlapping of the R.I. S.G. relationships for the various tektites (text fig. 10) according to Barnes (1940a, p. 520).

Refractive index and specific gravity values of tektites are functions of their chemical compositions. These relationships are indicated in text figures 11 and 13.

WEIGHTS OF TEKTITES.

Including fragments and complete or nearly complete forms of the various types of tektites, several tens of thousands of grams of tektite glass have been collected. Tektites have been recorded as weighing between one gram and occasionally one hundred grams (Watson, 1935). A large number do occur within this range, but many complete specimens are known to weigh less than one gram and a considerable number weigh over 100 grams. For example, one complete sphere of tektite glass from the Philippine Islands, almost perfect in shape and measuring four inches across, weighs 1,070 grams, while more than one hundred specimens of the Philippine Islands tektites weigh individually between 200 and 700 grams. Then again, half a dozen australites are known that weigh over 100 grams, the largest weight so far recorded being 218 grams for a specimen in the Perth Museum which was found at Lake Yealering in Western Australia. The smallest australite so far recorded is a thin, plate-like specimen from Port Campbell, Victoria, which weighs only 0·06 grams (Baker, 1946, p. 51).

The smallest and the largest recorded weights of the various tektite groups are listed for comparison in Table 4. Unfortunately it is seldom stated in tektite literature whether the weights for many specimens in these groups refer to complete forms only, or whether fragments are included, and average weights are seldom given; evidently because of considerable variability. The greatest weight cited for the indochinites, refers to a large piece from Lower Laos, F.I.C., and the least weight is for that of a fragment from the same area.

Table 3 lists the refractive indices, colour, specific gravities and hardness of tektites so far recorded in the available literature. The tektites are listed in this table according to an order of increasing refractive index.

TABLE 3.

Tektite Type and Locality.	n_{Na}.	Specific Gravity.	Hardness.	Colour.	Reference.
TRUE TEKTITES.					
Moldavites, Bohemia	1·4812–1·4956	2·303–2·364	..	.. ..	Jezek (1910)
Moldavites, Moravia	1·4856–1·4929	2·317–2·357	..	.. ..	Jezek (1910)
Moldavites ..	1·488 ..	2·303–2·364	6	.. ..	Verbeek (1897)
Moldavites ..	1·480–1·496 ..	2·303–2·367	..	.. ..	Tilley (1922)
Moldavites ..	1·48–1·6 ..	2·3–2·6 ..	5·5	Bottle green ..	Kraus and Slawson (1939)
Australites ..	.. ..	2·41–2·52 ..	6–7	Yellowish-brown	Moulden (1896), Stelzner (1893)
Australites ..	1·488 ..	2·45–2·47 ..	..	.. ..	Twelvetrees and Petterd (1897)
Australites ..	1·498–1·520 ..	2·386–2·453	..	.. ..	Tilley (1922)
Australites ..	1·505–1·510 ..	2·31–2·51 ..	6	Black to yellowish-green	Baker and Forster (1943)
Australites, Harrow, Vic.	1·515 (average of two)	2·386–2·468	..	.. ..	Baker (1955b)
Australites, Nirranda, Vic.	1·512 (average)	2·36–2·47 ..	..	.. ..	Baker (1956)
Australites, Port Campbell, Vic.	1·514 (average)	2·43 ..	..	.. ..	Baker (1956)
Bediasites ..	1·488–1·512 ..	2·334–2·433	..	.. ..	Barnes (1940a)
Malaysianite, Pahang, Malay States	1·505 ..	2·433 ..	..	.. ..	Tilley (1922)
Indomalaysianite, Laos, French Indo-China	1·5063 ..	2·422 ..	..	Brown ..	Lacroix (1931)
Javaite, Solo, Central Java	1·5091 ..	2·431–2·452	..	Brown ..	Heide (1939)
Tutong Station, Brunei, Borneo	1·5097 ..	2·457 ..	6	Dark greenish-brown	Mueller (1915)
Malaysianite, Kuala Lumpur, Malay Peninsula	.. ..	2·46			
Philippine tektites ..	1·5113 ..	2·439–2·444	..	Dark brown ..	Heide (1938)
Kwang - Chow - wan, China	1·5120 ..	2·440 ..	..	Brown ..	Lacroix (1931)
Billitonites ..	1·513 ..	2·420–2·503	6	.. ..	Verbeek (1897)
Rosario, Philippines	1·5130 ..	2·447–2·451	..	Brown ..	Lacroix (1931)
Paracale, Luzon, Philippines	.. ..	2·46–2·48 ..	..	Grey to dark green	Winderlich (1948)
Ivory Coast ..	1·4991–1·5178	2·40–2·517	..	Brown ..	Lacroix (1934)
DOUBTFUL TEKTITES.					
Macusani, Peru ..	1·486 ..	2·35 ..	..	Brownish-green	Heide (1936)
Paucartambo, Peru	1·4855 ..	2·3595 ..	..	Green to brown	Linck (1926)
Cali, Colombia ..	1·4853 ..	2·344			
Clifton, Arizona ..	1·4871 ..	2·355			

The smallest recorded tektites are said to be from Santa Mesa, Philippine Islands, where Beyer, (1935) referred to forms the size of a match-head. No weights of such tiny forms were given, and it was not stated whether they were complete shape types or fragments.

The upper weight for malaysianites in Table 4, refers to ball-shaped forms. The lowest weight cited for the Java tektites is for that of a thin potsherd form. The weight range for the australites refers solely to complete individual forms, but there are several small fragments known to weigh less than 0·06 grams. The average weight value for the australites varies from collection to collection, partly owing to the depletion of the larger and more perfect specimens from some collections prior to scientific examination. Thus, the average weight of 3,920 specimens comprising the W. H. C. Shaw collection of australites is just under 1 gram (Fenner, 1934, p. 77), while that of 7,184 specimens in the John Kennett collection has been determined as 6 grams (Fenner, 1940, p. 306). The average weight of 34 australites from Harrow, Victoria (Jones collection) is 8·97 grams, (Baker, 1955b), that of 366 specimens from the Nirranda Strewnfield, Victoria is 1·83 grams (Baker, 1956), but this includes fragments as well as complete forms, the complete forms averaging 2·560 grams (for 155 specimens). Among other collections of australites, those from Port Campbell, numbering 1,550 specimens, possess an average weight of 2·734 grams for 212 weighed complete or nearly complete specimens. The average weight of fifteen complete forms from Moonlight Head, Victoria is 4·912 grams, while the average weight for many australites of all shapes from all parts of Australia, excluding badly fragmented forms and pieces, has been calculated as approximately 1·5 grams (Baker and Forster, 1943, p. 393). Such variations will serve to indicate the difficulty of obtaining a reasonable average weight value for australites as a whole. However, little significance attaches to obtaining an average weight value, since among the various australite shape types, there is considerable weight variation. Of greater significance are the relationships between the weights and the specific gravity values of both individual australites and between the several shape types. It

TABLE 4.

Showing recorded weights of true tektites and of doubtful tektites.

Tektite Type.	Locality.	Smallest Recorded Weight in Grams.	Largest Recorded Weight in Grams.	Reference.
TRUE TEKTITES.				
Ivory Coast tektites ..	West Africa		79	Lacroix (1934b)
Bediasites	Texas, U.S.A. ..	0·5	91·3	Barnes (1940a)
Australites	Australia and Tasmania	0·06	218	Fenner (1934), Baker (1946)
Moldavites	Moravia		235	Kaspar (1938), Oswald (1936b)
Moldavites	Bohemia		500	Kaspar (1938)
Malaysianites	Kelantan, Malay States		464	
Javaites	Java, Dutch East Indies	0·9	750	von Koenigswald (1936), Heide (1939)
Rizalites	Philippine Islands ..		1,070	Beyer (1935, 1940)
Indochinites	Cambodia, Laos, &c. ..	1·0	3,200	Lacroix (1929, 1931, 1934a), Beyer (1935, 1940), Heide (1938)
DOUBTFUL TEKTITES.				
Macusani glass ..	Peru	9·0	375	Heide (1936)
Paucartambo glass ..	Peru		470 (1 sp.)	Linck (1926a)
Colombian glass spheres	Colombia, S. America ..	12·0	30	Codazzi (1925)

has been found that australites with the higher density values are equally as numerous among small as among larger forms (Baker and Forster, 1943, p. 403), so that for australites in particular, tektite glass of similar density is distributed among these objects irrespective of the final size or shape of individual forms, thus suggesting derivation from an originally well-mixed, relatively homogeneous glassy source.

Total weights of tektite material collected from the various strewnfields in different parts of the world, are also largely unknown. A total weight of over 120 kilograms is known to have been discovered in Indo-China (Lacroix, 1929, 1931, 1934a, 1935a; Heide, 1938; Beyer, 1935, 1940).

SPECIFIC GRAVITY.

Most work concerned with the specific gravity values of tektite glass, has been conducted with australites and some with moldavites and bediasites, but the other tektite groups have received little attention in this direction.

Wide variations of from 2·395 to 2·70 for the specific gravity values of australites were obtained by earlier workers (Clarke, 1855, p. 403; Ulrich, 1866, p. 65; Moulden, 1896; F. M. Krausé, 1896, p. 214; Stephens, 1897; Twelvetrees and Petterd, 1897; Stelzner, 1893; Walcott, 1898; Baker, 1900; Mingaye, 1916). The highest value given is much too high for australites and was evidently determined on a foreign object closely resembling an australite in external appearance. This is evident from Stephens (1897) remarks concerning a specific gravity value of 2·7 for a specimen from the Turon River in New South Wales, for Stephens argued that the specimen must have been composed of basaltic glass rather than obsidian (australites being regarded at that time as terrestrial obsidian). Many of the earlier specific gravity determinations for australites were determined from a few specimens obtained in widely separated parts of the vast australite strewnfield, and no particular specific gravity value could thus be taken as an average for australites as a whole. By combining the more reasonable of the earlier determinations with the many recently obtained values, a more accurate gauge of the *true range* and *mean* specific gravities results, principally because a larger number of specimens representing many centres of concentration and widely dispersed areas are taken into account.

Recent determinations of over 1,000 specific gravity values of australites (Baker and Forster, 1943) reveal a range of 2·305 to 2·510 and a mean of 2·410. The values for specimens known to contain gas bubbles of considerable size were excluded from these determinations. Inclusions of gas markedly affect the specific gravities of individual australites containing bubbles 2 mm. and over in size (Baker and Forster, 1943, p. 387). Such specimens have to be neglected in comparative work, or else the specific gravity has to be determined for the glass in the powdered state. Much smaller gas pores in australites affect the values in the second decimal place, as shown by comparing determinations on complete specimens (2·403) and on powdered tektite glass (2·423) of the same specimens. It is impracticable and unnecessary to powder all complete forms for specific gravity purposes, and it is sufficiently accurate to use the *mean* values for groups of tektites in comparative work.

The variation in the content of microscopic gas bubbles is of no significance from shape type to shape type among australites, nor from locality to locality, when the *mean* values of a statistically significant number of specimens are employed. Elimination of the effects of small gas inclusions by crushing

specimens and determining the specific gravity of the powdered glass, does point to a significant change that can only represent a true difference caused by chemical variations in the glass itself. Although variability of gas content in australites contributes to variations in *individual* specific gravity values within any given shape type or locality group, it is not as important a factor as chemical variation when the *mean* specific gravity of each particular group is considered. It is therefore *mean* specific gravity values with statistical significance that should be compared and contrasted in groups of tektites.

Another factor that has to be considered, but is difficult to assess from tektite to tektite, is the effect of strain in tektite glass on density. The density of glass increases when annealing processes remove strain (Hammond, 1950, p. 272). Few tektites are perfectly homogeneous, most show evidence of a little strain as proved by examination of thin sections of tektites under the polarising microscope, using a sensitive tint plate. However, the variations in strain from tektite to tektite are scarcely likely to affect density values other than in the third decimal place, and hence have little bearing upon the generalizations set out above, where variations in chemical composition are more significant.

Careful determination of the specific gravity of a tektite should give an approximate and quick idea of its chemical composition, once a good series of chemical analyses have been obtained, since the specific gravities of australites vary inversely as their silica content varies. Such determinations for six samples from each of four localities, led to the grouping of australites (Summers, 1909, p. 437) on a specific gravity—locality basis of analysed specimens thus:

TABLE 5.

A—Peake Station type	sp. gr. under 2·390
B—Hamilton type	sp. gr. 2·391 to 2·410
C—Mt. Elephant type	sp. gr. 2·411 to 2·440
D—Kalgoorlie type	sp. gr. 2·441 to 2·470
E—(?)Uralla type	sp. gr. over 2·470

This grouping was criticized (Lacroix, 1932) on the grounds that differences were slight and only a small number of specimens was used for such a large area of occurrence. Nevertheless, groups C and D (Table 5) were considered by Lacroix to be essentially the same in composition as tektites from the Far East.

Detailed study (Baker and Forster, 1943, p. 405) of over 1,000 specific gravity determinations of australites of total weight in excess of 1,000 grams, has shown the unsoundness of constituting definite australite types on a specific gravity—locality basis when less than ten individual specific gravity values are considered. It is statistically sound, however, to constitute australite types on the basis of their *mean* specific gravity values, obtained by averaging ten or more determinations, and in this way the comparative grouping in Table 6 has been obtained.

Statistical significance attaches solely to localities in italics in Table 6, since in them only, were numbers of determinations sufficiently large. There are limitations to this grouping, because account is not taken of the effect a preponderance of a given shape type might have on the specific gravity values. The William Creek population of australites, for example, is composed mainly of core-shaped forms, the Mulka population principally of lenses, boats and

cores, that from Port Campbell comprises an average collection of all shapes of australites, but with cores in the minority compared with the William Creek population.

TABLE 6.

Range in *Mean* Specific Gravities.	Localities.
2·350–2·379	Curdie's Inlet; Stony Creek Basin in the Grampians, Victoria
2·380–2·409	*Port Campbell; Hamilton; Balmoral;* and the Western District of Victoria generally
2·410–2·429	*William Creek; Mulka; Oakvale Station; Peake Station; Harrow;* Telangatuk East; Corop; Caramut; Ellerslie; Kaniva; Pieman River; Bulong; Macumba Station
2·430–2·449	*Charlotte Waters; Coolgardie;* Lady Julia Percy Island; Mt. Elephant; Polkemmet East; Inverell; Norseman
2·450–2·479	*Ooldea; Kalgoorlie;* Mt. Leura; Upper Weld; Nullarbor Plain

Neglecting specimens with specific gravity values significantly affected by included gas, it can be illustrated that localities with a sufficiently large number of determinations show significant differences between their represented shape types. Such differences can only be due to slight variations in chemical composition among the locality groups.

The frequency polygon, figure 12, shows the nature of the distribution of over 1,000 specific gravity determinations of australities from various parts of the continent, the mode occurring at 2·40.

Significant variations among the australite shape types from locality to locality, show there are real variations across the Australian continent, adding proof to Summers' (1909, p. 437) theory of the provincial distribution of australites according to their chemical composition, and upholding theories of extra-terrestrial origin, since no terrestrial method is known whereby provincial distribution could be effected over so large an area. No distribution according to chemical composition can be shown, however, in any one small centre of australite concentration, and it can only be advocated when considerable distances are involved between the end members in the australite strewnfield.

Little detailed work has been done on the specific gravities and their relationships for other varieties of tektites. Martin (1934) made a number of determinations on specimens from several localities, and suggested that the lower specific gravity values occurred in the centres of areas of distribution. This suggestion is by no means in accord with the distribution of australite specific gravity values.

Many individual specific gravities have been determined for moldavites, and F. E. Suess (1900) gave their range as 2·318 to 2·385, with most values between 2·34 and 2·36. Kraus and Slawson (1939) gave the range as 2·3 to 2·6, but their upper limit is much too high. Using a Preston Density Comparator, Hammond (1951, p. 271) obtained an average value of 2·3689 (at 20°C.) for three moldavites.

The specific gravities of five Philippine Islands tektites were noted as ranging from 2·441 to 2·448, with an average value of 2·444 (Hodge Smith, 1932, p. 583). Compared with the available values for australites and billitonites at that

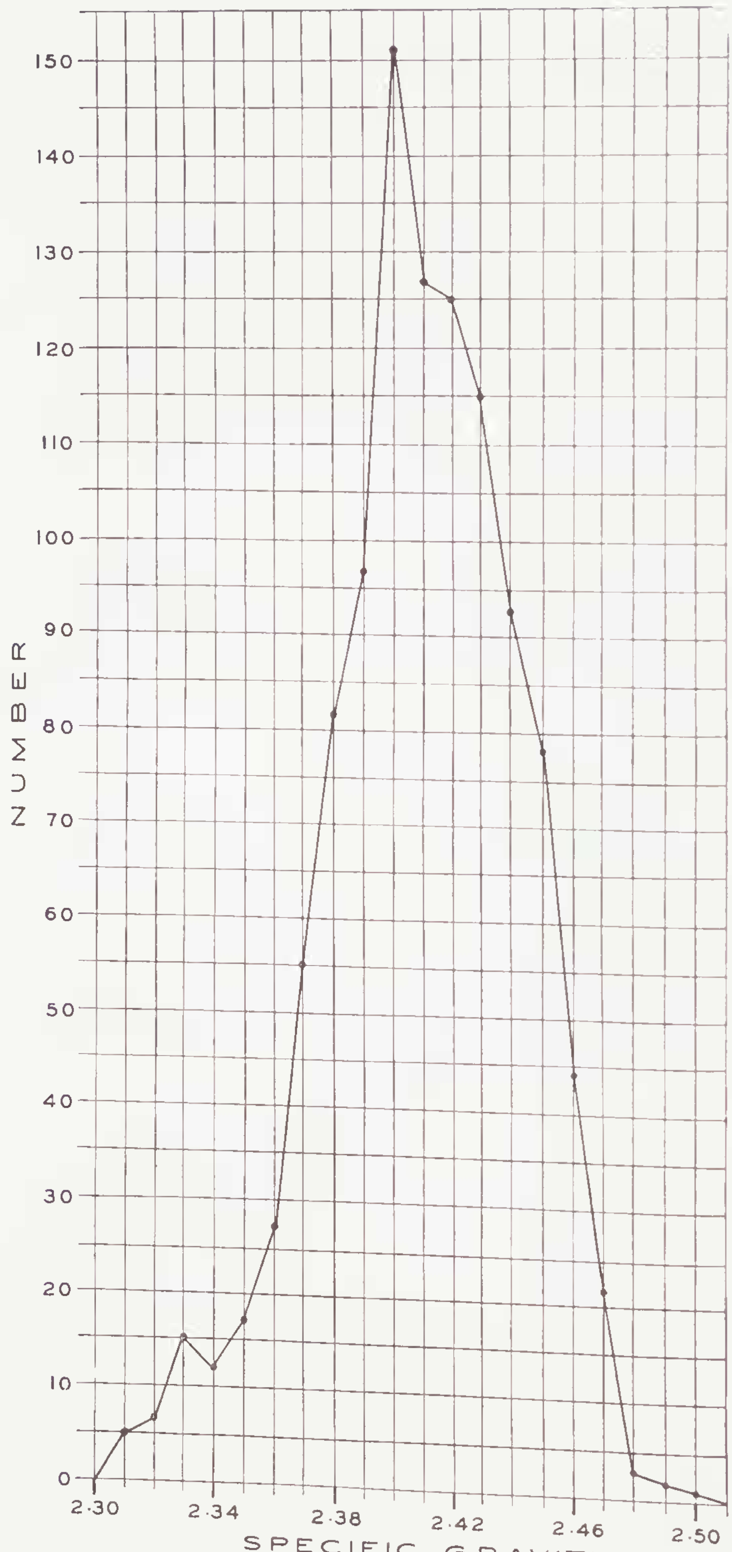

FIGURE 12.—Graph showing specific gravity distribution for over 1,000 australites of various shapes from different parts of Australia (after Baker and Forster, 1943).

time, Hodge Smith concluded that the specific gravity values of the Philippine Islands tektites would not serve to differentiate them from australites and billitonites, but their values were quite distinct from those of the moldavites.

Careful specific gravity determinations of 79 specimens of bediasites (Barnes, 1940a, pp. 499-500) revealed a range of 2·334 to 2·433 (average 2·374). Porosity is a negligible factor in these specific gravity variations, the main factor accounting for the range in values being variation in chemical composition.

The ranges in values and the mean specific gravity values determined for the various groups of tektites by several workers, are listed in ascending order in Table 7:—

TABLE 7.

Tektite Type.	Number of Determinations.	Mean Specific Gravity.	Range in Specific Gravity.
TRUE TEKTITES.			
Moldavites, Bohemia and Moravia ..	?	2·337	2·30–2·39
Bediasites, Texas, U.S.A.	79	2·374	2·334–2·433
Australites	1,086	2·410	2·31–2·51
Siam tektites	2	2·419	2·41–2·43
Indochinites	?	2·427	2·40–2·45
Rizalites, Philippines	5	2·441	2·43–2·45
Java tektite	1	2·442	—
Javaites, Solo, Java	?	?	2·431–2·452
Billitonites, Bulacan Province, Philippines ..	5	2·444	2·441–2·448
Ivory Coast tektites	?	2·451	2·40–2·52
Billitonites, Billiton Is.	5	2·456	2·43–2·48
Billitonites, Billiton Is.	?	?	2·420–2·503
Malaysianite, Kuala Lumpur	1	2·46	—
DOUBTFUL TEKTITES.			
Colombian (?)tektites, Cali, Colombia ..	?	2·344	—
Macusani (?)tektites, Peru	?	2·35	—
Paucartambo (?)tektite, Peru	1	2·408	—

Comparisons of available determinations for all accepted tektites, show that specific gravity values indicate moldavites and bediasites as the more acid members of the tektite family. Having lower mean specific gravities than australites, they are more acidic on the whole, although the lower limit in the range for australites overlaps that of both moldavites and bediasites. Moldavites and bediasites are of comparable acidity. On the same basis, javaites, indochinites and rizalites are more basic than australites, occupying positions intermediate between them and the still more basic billitonites. Ivory Coast tektites and billitonites complete the series in having the highest specific gravity values, and they are thus the most basic varieties of all tektites. These conclusions are borne out in some measure by the chemical analyses listed in table 15, although there are certain anomalies. Because of paucity of numbers of analyses of some varieties, however, the actual relationships are not always clear.

Individual specific gravity values of analysed tektites plotted in fig. 13, show their relationships to silica content. Natural glasses such as Libyan Desert glass, Darwin Glass and lechatelierite, which are all probably of terrestrial origin, are also included for comparison.

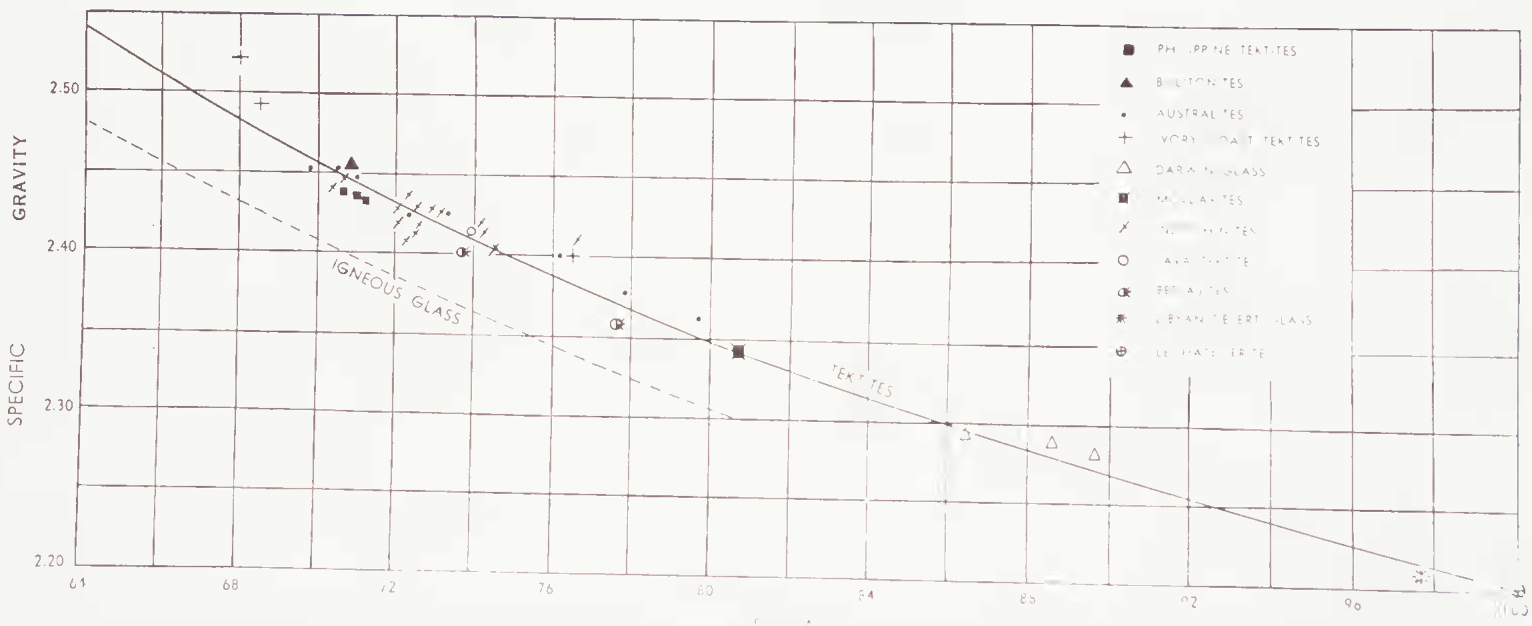

FIGURE 13. Variation diagram showing relationship between specific gravity and silica content of tektites and silica glass, compared with that for igneous glass (after Barnes, 1940a).

The range in the australites shows the necessity for obtaining mean values when comparing the separate tektite groups one with another. The curve for igneous glasses in fig. 13, was modified (Barnes, 1940a, p. 544) from the work of W. O. George *

This curve is lower than the tektite curve. When the curve for the relationship of SiO_2—Specific Gravity (also that for SiO_2—Refractive Index in fig. 11) is used in conjunction with tektite variation diagrams (figs. 26 and 27), an approximate chemical composition can be derived for a tektite of known specific gravity and refractive index. The trend of the relationships shown by the curve for the tektites in fig. 13, is fundamentally similar to the general trend outlined for specific gravity values listed in Table 7.

HARDNESS.

Various writers record the hardness of moldavites as falling between 6 and 7 on Moh's Scale. For billitonites it is 6 (Verbeek), while australites vary from 6 to 7 (Moulden, 1896).

In terms of the "per mille" hardness of corundum, the hardness of moldavites, as determined by A. Rosiwal, is compared with that for artificial glass, quartz, felspars and pitchstones in Table 8 (cf. Suess, 1900).

TABLE 8.

	Specific Gravity.	Average "per mille" Hardness.
		%
Moldavites, Skrey	2·344	31·0
Moldavites, Budweis	2·363	29·5
Green Glass	2·268	19·8
White Plate Glass	2·546	18·2
Liparite Obsidian, Mexico	—	34·2
Obsidian, Yellowstone Park	—	35·6
Felsite-pitchstone, Meissen, Germany	—	21·4
Felsite-pitchstone, Arran	—	25·5
Oligoclase felspar	—	35·5
Orthoclase felspar	—	39·6
Quartz	—	117·0

The "per mille" hardness is higher for moldavites than for the artificial glasses, but lower than for obsidians, felspar and quartz.

The hardness of indochinites is 6 on Moh's Scale, the same as silica glass, but the indochinites are slightly softer than billitonites and australites (6 to 7) and Darwin Glass (7 according to Loftus Hills, 1915, p. 9) which scratch quartz. Fragments of australites scratch many varieties of artificial glass and also orthoclase, but are sometimes marked with difficulty by quartz.

BEHAVIOUR OF TEKTITES TO HEAT TREATMENT.

Tektites are liquids endowed with a viscosity so great that they behave like solids at ordinary temperatures. Experiments on the reactions of various tektites to heat treatment show that rise of temperature causes different degrees

* W. O. George—"The Relation of the Physical Properties of Natural Glasses to their Chemical Composition," Journal of Geology, vol. 32, pp. 353-372, 1924.

of deformation according to composition (Lacroix, 1932). Tektites have no definite fusion points, but gradually become soft and then sufficiently fluid to spread out and take the shape of containing vessels. A dilatation curve for a Tan-hai Island tektite is compared with that for ordinary glass in fig. 14.

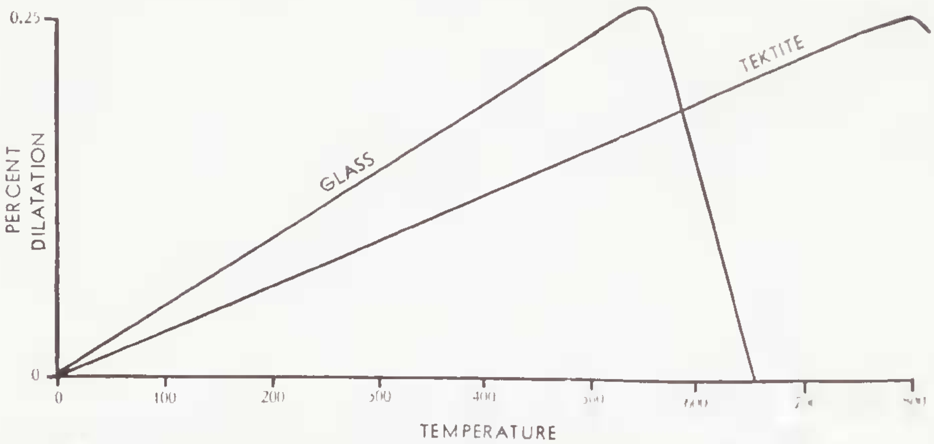

FIGURE 14.—Dilatation curve for an indochinite from Tan-hai Island, compared with that for ordinary glass (after Lacroix, 1932).

Deformations of the tektite commenced at 800°C., ordinary glass a little before 600°C.

The tektites from the Far East are most fusible, followed by australites and then moldavites. Darwin Glass, now considered to be non-tektitic *sensu stricto*, is more resistant to heat treatment than the true tektites. There is a corresponding variation of chemical composition, specific gravity and hardness with variation in fusibility, the most difficult tektites to fuse are the more acidic varieties, which are also the least dense and the hardest.

The available temperatures of fusion for the different groups of the tektite family, have been assembled in Table 9.

Softening temperatures comparable with those for the billitonites and indochinites are not available for the other tektites, but experiments by Lacroix (1932) indicate the temperatures at which prepared shapes of different tektites would flow sufficiently to imitate teardrop and dumb-bell shapes. Test samples were cut and ground to produce weight and dimensions approximating the natural weight and size of a selected indochinite. The test pieces were suspended with a platinum wire from a refractory bar and heated in a Surface Combustion Furnace (gas and air blast), with slow, regular temperature rises controlled at 200°C., each half hour. Good resemblances to the natural shape of the indochinite were obtained by arresting the furnace temperature at intervals. Tektites from Tan-hai Island, from Mt. William in Victoria, from Billiton Island and from Radomilice in Bohemia, as well as Darwin Glass, were placed side by side in the experiment. The billitonite flowed completely when the onset of stretching commenced at 1,190°C., but the australite had only commenced to elongate. The Tan-hai Island tektite behaved like the billitonite, the Bohemian moldavite softened on the outside and commenced to stretch, but Darwin Glass remained unchanged. At 1,180°C., the Tan-hai Island tektite passed

into the form of a dumb-bell, the moldavite stretched at 1,250°C., slowly flowed and fell down at 1,370°C. Darwin Glass was most resistant, stretching at 1,400°C., and flowing down at 1,450°C.

TABLE 9.

Showing the Fusion Temperatures of Tektites.

Tektite.	Softening Temperature.	Fusion Temperature.	Reference.
TRUE TEKTITES.			
Billitonites	806° C.	1,055° C.	Beck (1910)
Indochinites, Northern Cambodia	750° C.	1,200° C.	Lacroix (1929, 1932)
Australites	..	1,324° C.	Grant (1909)
Moldavites	..	1,400° C.	Bares (1899), Suess (1900), and Kaspar (1938)
Moldavites	..	1,300° C. to 1,500° C.	Hanus (1928)
DOUBTFUL TEKTITES.			
Colombian (?)tektite	..	1,100° C.	Stutzer (1926)
Paucartambo (?)tektite ..	..	1,200° C.	Linck (1926)
REJECTED FROM TEKTITE GROUP.			
Darwin Glass	..	1,450° C.	Lacroix (1932)

It had been shown earlier (A. Brun) that a billitonite bent at 806°C. on the application of pressure and bent spontaneously without pressure between 871°C. and 883°C., melting and flowing into the containing vessel at 1,055°C. Similar results were obtained by Wing Easton, namely 800°C., 880°C., and 1,050°C. for the softening and fusibility of billitonites.

Further fusion tests as applied to the various types of tektites are outlined in Chapter XV.

The coefficient of linear thermal expansion of a moldavite containing 78·46 per cent. SiO_2, 12·34 per cent. R_2O_3, 4·82 per cent. CaO and MgO, 3·82 per cent. K_2O and Na_2O, 0·06 per cent. MnO and 0·32 per cent. TiO_2 (total = 99·82 per cent.), has been calculated as 29·9 x 10^{-7} cm. per cm. per degree Centigrade (Hammond, 1950, p. 274). This value is 3 x 10^{-7} less than for pyrex glass and 60 x 10^{-7} less than for ordinary container glass, indicating that moldavite glass has greater resistance to thermal shock than ordinary glass, and can be cooled rapidly without the development of excessive strain.

It has also been shown (Hubbard, Krumrine and Stair, 1956, p. 772) that australite glass has low expansion characteristics and a high deforming temperature, and that it has similar properties to a group of artificial glasses classed as superior, inasmuch as the hygroscopicity is low, its chemical durability is good, the heterogeneous equilibria at solution-glass interface is good, and the pH response of australite glass electrodes is negligible. Such factors all add up to providing australites with a maximum chance of survival during their rapid transit through the earth's atmosphere, and subsequently during the few thousand years that they have lain upon the earth's surface.

Further to the work that has already been accomplished regarding the behaviour of tektites to heat treatment, it is to be hoped that modern techniques and appliances may be employed in furthering the solution of several problems peculiar to tektites. Thus, as already indicated by Hubbard, Krumrine and Stair (1956, p. 778), the continued use of the interferometer and other dilatation procedures for determining the expansion curves and critical temperatures of tektites from different showers, may provide useful information for comparing and contrasting the thermal shock characteristics with the average size of tektite specimens. Furthermore, the application of procedures for studying viscosity, surface tension, working temperatures, liquidus and other phase equilibria data of tektite compositions, may provide significant results relating to the development of both primary and secondary structure features and flow patterns of the different varieties of tektites.

CHAPTER IV.

EXTERNAL FEATURES OF TEKTITES. EXTRANEOUS MATERIALS ATTACHED TO TEKTITES. THE FLANGES OF AUSTRALITES. THE CURVATURE OF TEKTITE SURFACES.

The characteristic surface features of tektites are bubble pits, flow lines, grooves, and in australites, flow ridges. Tektites without some of these features have either been recently broken and fragmented or else subjected to considerable abrasion by wind or water action. Secondary features associated with certain tektites are the flanges on australites, and soil, sand, clay, limonite, manganese dioxide and limestone cemented on to parts of the surfaces of many specimens from several of the various zones of distribution. An important characteristic of the australites is the nature of the curvature of posterior and anterior surfaces, and the relationship of the radii of curvature of these two opposite surfaces.

EXTERNAL FEATURES OF TEKTITES.

Moldavites.

Pits and grooves on external surfaces of tektites are frequently referred to as constituting their " sculpture ", a comprehensive description of which was rendered by F. E. Suess (1898 and 1900) for the moldavites. Certain impressions resemble shallow fingerprints, others are rounded and oval, shallow cup-shaped depressions up to the diameter of a pea, and yet others consist of numerous smaller pits (Plate III).

The smaller pits have been likened to the marks produced on lead by gunshot, as developed in an experiment conducted by A. Daubrée. Other pits are deeply excavated, sometimes with smooth walls, but sometimes covered with numerous smaller pits. Deeply engraved, narrow sharp-edged rills and canals cover the whole surface of many specimens. These are often arranged in star-like fashion, spreading from the centre of the surface towards the edges (Plate IV).

The sculpture patterns of moldavites are related in various ways to their shapes. Pear- or drop-like moldavites possess plumose furrows on their elongated portions (tails); the furrows follow the axes of the tails in central portions, but curve outwards near edges. Some of the moldavites show small grooves inside larger grooves, arranged at right angles to the trends of the larger; these have been referred to as " fiederung " by F. E. Suess. There is little in common between the sculpture of the moldavites and the surface structures of metallic meteorites (Berwerth, 1910).

Australites.

Australites rarely have identical markings on both their posterior and anterior surfaces, and in this feature they present a differentiating characteristic from the great majority of specimens of all the other types of tektites. A few of the australites with similar surface features on both surfaces, are types that have evidently been subjected to abrasion and a degree of natural etching. In this way, one or two flanged buttons and occasional lens-shaped australites from Port Campbell and from Nirranda in Victoria (Baker, 1955) have come to possess equally and finely bubble-pitted posterior and anterior surfaces. In attaining this condition, the original flow ridges so typical of the anterior surface of australites, have been lost by abrasion, and

the newly exposed surface subsequently finely pitted by natural etching agents. Such fine pitting has extended on to the usually smoother, delicately flow-lined posterior surfaces of flanges. Another rather unusual feature of australites is possessed by an interesting "aberrant" form in the Melbourne University Collection. This form, which is somewhat different in shape from the normal canoe-shaped australites, has similar grooves on both surfaces (Singleton, 1939). A few forms of australites also possess flow ridges on both surfaces (Fenner, 1934, p. 74). Since these flow ridges are generally typical of anterior surfaces, it is suggested that such forms changed direction during atmospheric flight, so that the anterior surface at some stage, became posterior to the object, and vice versa. A large boat-shaped australite from Corop, northern Victoria, and a core from the Kalgoorlie district of Western Australia, are unique in possessing several drawn-out, star-like clusters of grooves (Plate I, fig. L) on the posterior surface (Baker, 1940). Each cluster is compressed and rather distorted in the direction of the long axis of the core. Such grooves are usually confined to anterior surfaces or flaked equatorial zones when present on australites. Australites showing anomalies such as these, however, are relatively few in number compared to the large numbers with normal characteristics.

In addition to concentrically arranged "flow" ridges recognized early in studies of australites (e.g., Stelzner, 1893), some on button-shaped specimens and on occasional lens-shaped forms are observed to be spirally arranged on the anterior surfaces. These may be clockwise or anti-clockwise in sense, and follow the general curvature of the anterior surfaces, being narrower in the front polar regions and broader at the back (i.e., towards the equatorial peripheries). They thus have the forms of right and left helical spirals. These ridges often become wrinkled near the equatorial edges of anterior surfaces, apparently as a result of the running together of ridge-like portions of stiffer melted glass in those regions of the australites under the influence of frictional drag and partial fusion stripping. The distance from crest to crest of the "wave-like" structures between the "flow" ridges elsewhere on the anterior surfaces has been reported as very even and averaging 3 mm. apart (Fenner, 1934, p. 74). On the majority of well-preserved specimens from south-western Victoria, however, careful measurement has revealed that the ridges are invariably a little closer together near the equatorial peripheries of anterior surfaces than they are towards the front polar regions. Concentric "flow" ridges occur on approximately 50 per cent. of "flow"-ridged specimens, the remainder being equally divided between clockwise and anti-clockwise spiral ridges. One rare example has been observed with a double clockwise spiral flow ridge, so arranged as to simulate the arms in a spiral nebula (Baker, 1956).

The bubble pits on australites are sometimes circular, sometimes elongated in outline, and are usually so abundant on posterior surfaces as to form cellular, finely honeycombed surfaces (Plate V, fig. A).

In practically all other tektites, the pits are not confined to one particular surface as in australites, but are scattered over all surfaces. The walls of the larger bubble cavities in australites, are often covered with smaller bubble pits.

Flow lines ("schlieren") are as common on surfaces as within the interiors of tektites. On button-shaped australites, they occur radially (Plate VIII, fig. C) or in fold-like manner on anterior surfaces, as fine concentric lines on the chin and posterior surfaces of many flanges, and as circular and elliptical

areas (forming "swirls") on smoother portions of the usually bubble-pitted posterior surfaces of the central core (Plate V, figs. B and C). Flow lines usually trend parallel with the long axes of the elongated australites (Plate XV, fig. 5). They are narrow, shallow markings on tektites, and represent streaks of slightly different chemical composition and physical constitution to areas of non-flow-lined tektite glass. External (and internal) flow lines frequently open out into deeper grooves and bubble pits, evidently as a result of differential natural etching.

Flaked equatorial zones of the larger australites are often marked with complex flow-lined patterns and occasional bubble pits (Baker, 1940, p. 488), left on the surfaces by escaping gas, or depressions produced by etching. The structure of a flaked zone is well shown by an unabraded, boat-shaped core from Port Campbell, Victoria in figure A, Plate X. Whereas short bubble grooves in the flaked zone trend parallel with the short axis of this core, flow lines often cut obliquely, sometimes almost at right angles across the bubble groove surfaces.

Although the general characteristics of the sculpture components of australites are generally similar, they show minor variations from specimen to specimen, partly as a result of their state of preservation, partly as a result of their accentuation by natural etching processes. In several, such variations are controlled by the shape and size of the specimens. Early descriptions of the surface features of australites recorded circular ridges as being parallel to the equatorial rim (Stelzner, 1893). Some of the ridges have a wavy course and occasionally merge with one another, some are sharp-edged. Streaks running radially across the ridges, are fine flow lines. The fact that these flow lines never parallel the flow ridges, and are invariably radial from front polar regions outwards, points to the fact that australites probably did not rotate during flight as has always been advocated up till now. Numerous bubble pits, up to 1 mm. across and approximately half a millimetre deep, are sometimes arranged in rows, sometimes crowded together in large numbers, and occasionally they occur singly. The walls of these pits are seldom absolutely smooth; even the smoothest are observed to possess fine striae when examined under a binocular microscope, and many show flow lines to the naked eye.

On a hollow australite sphere from Kangaroo Island, South Australia, larger radially arranged, elongated scars replace smaller, less ovate pits towards the equator of the less curved surface (Stelzner, 1893). This specimen is illustrated in Plate XIV, fig. 1b. On the larger, flatter half of another sphere, a network of small furrows concentrated around the pole, radiate outwards and fade away before reaching the equatorial regions.

These descriptions of a few of the varying patterns of external surfaces, indicate how minor sculpture elements develop in certain positions to different degrees on australites. The positions and nature of the sculpture components likewise vary from specimen to specimen in extra-Australian tektites.

Ivory Coast Tektites.

Cup-shaped cavities ("cupules"), smaller pits and "corrosion grooves" occur on the Ivory Coast tektites (Lacroix, 1934b). One specimen has been observed to possess a navel-like "cupule" resembling the "höfchen" on billitonites.

Indochinites.

The sculpture of indochinites has been described in detail by Lacroix (1932, 1935). Some forms possess large bubble cavities (Plate VI, fig. 2), others have hemispherical and hemi-elliptical pits the size of a pin's head (Plate VI, fig. 1), all referred to as "cupules". Canals ("cannelures") on the surfaces of other forms are deep as well as shallow in drawn-out portions (Plate VI, fig. 9). Grooves or gutters ("gouttières") are rarely rectilinear, more often vermiform and annular (Plate VI, fig. 3), but seldom as deep as similar features on billitonites and moldavites. Corrugations or puckers ("plissures") on some of the indochinites are closely-spaced, groove-like depressions that sometimes take on an anticlinal appearance (Plate XVIII, fig. 5). The "gouttières" are occasionally superposed on the "cannelures".

Rizalites.

The sculpture of the rizalites (Plate XIX) from the Philippine Islands consists of furrows, circular depressions and corrugations, the corrugations ("plissüren") indicating a streaky consistency (Heide, 1938). The flow pattern resembles that on the tektites from Siam, Central Java and French Indo-China. Some of the specimens from Luzon are finely pitted, referred to as "chicken-skin" pitting (Van Eek, 1939). Others from the Sitio of Pugad Babuy, municipality of Polo, Bulacan Province, Philippine Islands, show pitted surfaces with curved crevasses that are U-shaped in sectional aspect, sometimes circular in plan and forming an "island" (Hodge Smith, 1932, p. 581), and so are comparable to the "navel" or "höfchen" and "tischchen" structures on billitonites and on occasional of the Ivory Coast tektites. Similar, less frequent, smaller features like these occur on a small number of australites. Such grooves are regarded in some quarters as "schmelzrinnen" (Winderlich, 1948, p. 113), meaning "melt grooves".

Javaites.

Fine, deep radial cracks occur on the so-called flange of an oval-shaped Javanese tektite that is reported to be button-like and thus somewhat comparable with the more commonly developed shape type among australites. A fine, irregular "cracklin" structure appears on the anterior surfaces of other varieties of the Java tektites (Heide, 1939). Shallow pits, occasionally with a central cone, and short furrows are also present. Fine wrinkles on the posterior surface of one specimen are distinctly radial. Some specimens show minute pits following the trends of the wrinkles ("plissüren"), and others have a few deep "finger-nail imprints".

Bediasites.

The bediasites from Texas, U.S.A., show surface features (Plate VII, figs. 1 to 12) comparable with other tektites, although often not as strongly marked, evidently because of abrasion and spalling. Flow structures have been recorded that do not conform to the surfaces or shapes of the bediasites, being straight in part, curved and highly contorted in other parts (Barnes, 1940a, p. 502). The nature of such structures is by no means surprising in view of the generally spalled character and abraded, etched surfaces of fragmented tektites that show little evidence of well-developed primary or secondary shapes.

On pitted surfaces of the bediasites occur V-shaped furrows and "lunar craters" (U-shaped circular furrows), each surrounding a small knob of glass, comparable with the "höfchen" and "tischchen" of billitonites. Conical pits

on bediasites are up to 4 mm. in diameter, and similar in shape to the impressions created by sticking a lead pencil into a plastic mass. Bediasite surfaces pitted by shallow circular depressions so crowded that the intervening ridges are sharp, have been likened to the surface of a hammered metal.

South American (?)Tektites.

The Colombian (?)tektites possess rough, pitted surfaces and superficial irregularities of various kinds (Codazzi, 1929).

The sculpture of the crystal-bearing (?)tektite from Paucartambo (Plate XIII, fig. 1) consists of meandrine cavities and small pits with sharp edges (Linck, 1926a, p. 158). Curved, bay-like depressions and notches 1 centimetre deep and up to 2½ centimetres long, with smooth walls, have been likened to "knife-marks" and are comparable with structures referred to as "saw-marks" on australites.

EXTRANEOUS MATERIALS ATTACHED TO TEKTITES.

Reddish material in cracks, bubble pits and gap regions of australites, has been described as tuffaceous material gathered by the objects from a volcanic region (Walcott, 1898, p. 48). The original specimen examined by Darwin was thought to have been buried in "reddish tuffaceous material", but it was found in an area hundreds of miles removed from any known volcanic crater. Like that examined by Walcott, the material is most likely iron-stained clay. Thin sections cut from Port Campbell australites revealing similar such clay in gaps and cracks, show that quartz grains are embedded in the clay (Plate XI, fig. A). The clay is partially cemented to the australites by secondary iron hydroxide, and is identical with clay on which the specimens were found. This clay is the non-soluble residue of dissoluted Tertiary limestone, and thus in no way related to tuffaceous material. Where located on sand or soil, the substance in the cracks, gaps and bubble pits, is the same as that of the surface material upon or within which the australites rested. The white substance sometimes observed in the gap regions of small, disc-shaped australites, has been pronounced as silica (Dunn, 1916, p. 226) without any explanation as to its origin. Such siliceous material in the bubble pits and gap region of a perfect oval-shaped australite figured by Dunn (see Plate IX, fig. C of this monograph) is fine, clean detrital quartz that has been jammed into the gap region and bubble pit depressions, and partially cemented therein, as in many other examples found on areas with thin veneers of clean, white quartz sand.

Rizalites from S. E. Rizal Province, Philippine Islands, have surface grooves and pits filled with a hard manganese oxide deposit, where collected from superficial sediments containing nodular manganese ore (Beyer, 1934). Elsewhere in the Philippines, a soft white deposit resembling an oxide of tin, is embedded in the pitted surfaces of the rizalites. White clay in the "schmelzrinnen" of some of the Paracale rizalites, is regarded as decomposed felspar derived from granite (Winderlich, 1948, p. 113). Reddish-brown clay with detrital quartz grains also occurs in the pits and grooves on the surfaces of the rizalites. One specimen in the Melbourne University Geological Collection shows a narrow sliver of tektite glass broken from the walls of a groove and cemented in the hardened clay contained in the groove.

Lateritic material full of clastic grains has penetrated deeply into notches and other sculpture markings on indomalaysianites (Lacroix, 1932). In the Wentchang district, Island of Hai-nan, white clay with quartz grains occurs in

the grooves and pits on the tektites. The quartz was mechanically introduced, and not included in the glass, and is thus in no way allied to the origin of these tektites. Tektites from Sim San, district of Ting-an, Hai-nan Island, and from Smach in Cambodia, French Indo-China, are sometimes encrusted with limonite.

Dissected bubble cavities on Bohemian moldavites are sometimes filled with a mixture of quartz sand and reddish coloured soil (F. E. Suess, 1932). Other moldavites have cracks filled with yellow loam (F. E. Suess, 1900).

The different materials wedged or sometimes cemented into grooves, bubble pits and larger cavities, gap regions and cracks of the different types of tektites, were by no means concerned in the origin of the tektites. They are not products of decomposition of tektite glass, but are obviously secondarily introduced from deposits on which tektites fell, or into which they were subsequently swept. The secondary matter in the cracks, &c., is often incoherent and readily removed, but occasionally consolidated by ferruginous, manganiferous or siliceous cements. Differential expansion between tektite glass and material in the cracks during exposure, ultimately causes such tektites to break along the direction of the clay-, soil-, sand- or limonite-filled cracks.

THE FLANGES OF AUSTRALITES.

Darwin described the structure now known as the flange on australites as the "lip of the saucer" and remarked that it was slightly concave. The flange was likened to the margin of a soup plate and its inner edge was noted to overlap a little the central cellular portion (i.e., the core portion or body).

Flanges and rims are characteristics that place australites in a class distinct from other tektites (Fenner, 1934, p. 73). They are of secondary origin in the developmental history of australites. A mere projecting sharp edge of glass from the equatorial portion of some australites forms a *rim*, but when fully developed, the projection forms a *flange* (see Plate V, figs. D to F, Plates VIII, IX and XV, fig. 4). The presence of a rim or a flange on australites, or remnants thereof, indicates that virtually all specimens of these tektites underwent secondary fusion on the front surfaces. Only a precarious connexion occurs between flanges and the central cores of australites, as first clearly seen in Dunn's (1912b, plates 13 to 15) illustrations of sectioned button-shaped specimens. The internal structures of flanges are intimately associated with the internal flow patterns of body portions and such relationships are discussed in Chapter V.

Flanges are annular bands of glass projecting from the equatorial regions of such australites as buttons and some ovals, boats, teardrops, canoes and dumb-bells, and are particularly rare among tektites from other parts of the world, only an imperfect example so far having been recorded from one of the Java tektites. On australites, the flanges (and rims) separate the bubble-pitted posterior from the flow-ridged anterior surface, and are congruous in curvature with the anterior surfaces of central body portions (cf. Plate X, fig. B). The flanges vary in width from 1 to 6 mm., but may reach 9 mm. on exceptional specimens (Plate VIII). The average width is 4 mm.

The flatter plate- and disc-shaped australites, measuring 8 to 12 mm. in over-all diameter, have thin flanges 3 to 5 mm. wide (Plate V, fig. E) comprising 75 per cent. to 83 per cent. of the total width of the specimens. Most flanges are broad and thick, and usually curve over towards body portions on their inner edges, but rims, which occur principally on lenses and larger, unflanged core-like australites, are sharply defined, slightly projecting processes formed in

equatorial regions. Rims may ultimately develop into flanges during atmospheric flight, by the further flow of glass fused from anterior surfaces. Recurvature of the flange glass is usually such as to leave a gap (fig. 8C) between flange and body, but this glass was sometimes sufficiently fluid to be spread out over the equatorial peripheries of back surfaces (fig. 15) to form "crinkly-tops" (Fenner, 1934, p. 69).

Flanges are sometimes preserved in a complete state on buttons, but being the least mechanically stable structures of australites, they usually break away either during flight or while resting upon the ground. Rarely does the whole flange break away as a complete ring of australite glass (fig. 16S). Oval-shaped australites sometimes, and boats and dumb-bells rarely possess complete flanges (Plate IX). Many dumb-bells, teardrops, boats and canoes now pcssess no flange at all, but such specimens are usually weathered and have evidently had the flanges removed by erosion. Numerous specimens provide distinct evidence of this process having occurred.

As found on the earth's surface, canoes usually have flange structures preserved only at the tapered ends, boats only have remnants along their more or less parallel sides. In many dumb-bells, flange remnants are limited to the waist regions.

Posterior surfaces of most flanges appear smooth (Plate IX) to the naked eye, but higher magnifications reveal fine concentric flow lines on forms that have not been excessively abraded or too much naturally etched. The broad,

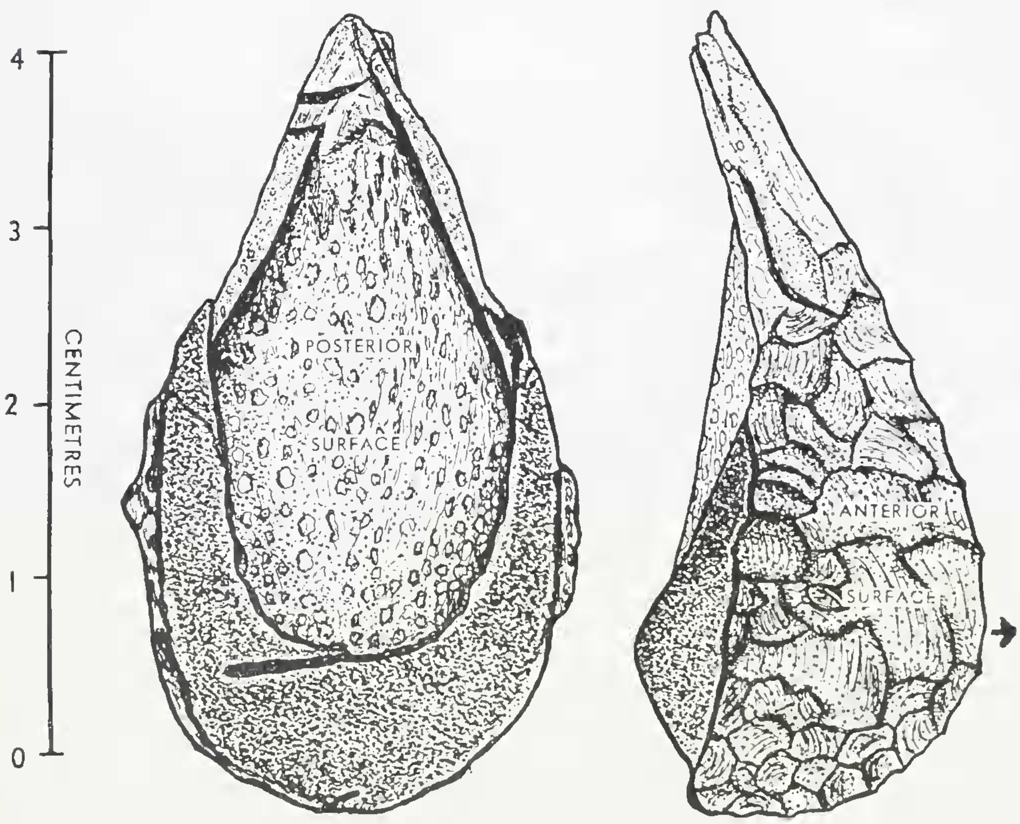

FIGURE 15.—Sketch diagram of tear-drop-shaped australite showing flange-building glass spread over edge of posterior surface in "crinkly-top" fashion, and new flange developed in parts. Flow ridges on anterior surface much wrinkled. From Port Campbell, Victoria. (Arrow on right indicates direction of propagation through the earth's atmosphere—cf. page 182.)

thin flanges of plate- and disc-shaped australites sometimes show concentric (fig. 16T), but more frequently radial flow lines, indicating that such forms did not rotate during flight through the atmosphere. Posterior surfaces of flanges are seldom bubble-pitted like the posterior surfaces of central body portions. When present on flanges, the few pits observed are caused by bursting gas bubbles, not by the impact of small spherical foreign bodies on semi-plastic australite glass as suggested by Walcott (1898, p. 36). Such pits are often regularly hemi-spherical and never contain adhering particles of the postulated foreign bodies.

Anterior surfaces of flanges form the equatorial limits of the anterior surfaces of body portions. Characteristic features are the wrinkled appearance of flow ridges (Plate IX, figs. A and B). The complex pattern of flow ridges on flanges partly accounts for the occasionally wavy nature of their outer edges (Plate VIII), which sometimes contrast markedly in plan with the smooth, even nature of inner edges ("chins"). Rare bubble marks on anterior surfaces of flanges differ from those on posterior surfaces. They are usually tube-like and stretched out parallel with radial flow lines that transect flow ridges, thus pointing to streaming of fused glass from anterior surfaces to equatorial regions. They often become accentuated under the influence of differential natural etching processes. Some circular bubble marks on the anterior surfaces, consist of crater-like depressions occasionally with a small cone-shaped pinnacle of glass forming a structure like the "höfchen" and "tischchen" structures on billitonites. The openings of these bubble marks on australites are often narrower than the diameters, suggesting collapse against pressure rather than bursting by expansion.

Surfaces of attachment between flanges and body portions of australites are best seen on complete or fragmented flanges that parted cleanly along lines of union. These surfaces are sometimes traversed by bubble tracks or are marked with numerous aggregates of shallow bubble impressions, indicating accumulation of gas bubbles in the contact regions. These accumulations materially weaken junctions between flanges and body portions. Variations in their amounts and positions of concentration, control the ease of detachment of flanges, thus accounting for the rare detached complete flanges (22 known), and the numerous flange fragments (over 300 known). Some flange fragments and complete flanges remain firmly attached to the central core and, in them, gas accumulations along the plane of contact are at a minimum.

The overhanging neck surfaces of flanges (fig. 8C) sometimes show finely marked concentric flow lines parallel to similar ones on the chins and posterior surfaces of the flanges. They all represent the "outcrops" of prominent internal flow lines (Plate XII).

The shapes of flanges in plan correspond with the outlines of the australite bodies on which they were formed. In cross sectional aspect they show a considerable diversity of shapes (figs. 16C to 16Q). Examination of sliced flanged australites (Baker, 1944, p. 11), reveals that no two flanges are quite alike, and indeed indicates some small variability of internal structure within one and the same flange. The generally coiled character of the internal flow lines of the annular band of glass constituting an australite flange, however, is a characteristic feature from australite to australite.

Growth of Flange Structures.

The initial phase of flange formation is the rim (fig. 16A), a mere projection representing an arrested stage of flowage of glass that reached the equatorial limits of the body from the superficially melting front polar regions during

flight. Increased supply of melted glass flowing from the anterior surfaces which are subjected to sheet fusion and some ablation, built up in the equatorial regions as the coiled flange structures. Some glass was undoubtedly lost during the process by ablation, and, towards the end stages of flight, by fusion stripping. Flanges continued to grow on some australites until a stage was reached when they became unstable and broke away from the body. Once lost, if secondary fusion and flowage of glass from the body portion continued, a new flange could commence to develop. Evidence for this is found in a few australites (Plate XI, fig. D) where the flight duration was sufficient, or the physical state such as to permit repetition of the process. No evidence is forthcoming of the process being completed more than twice during atmospheric flight.

Flanges solidified at various stages of development, as revealed by their shapes and degree of curvature variations on different forms (figs. 16E to 16M). Solidification occurred when the initial rim had been partially drawn out and recurved towards the posterior surfaces of some body portions (fig. 16C), or at any stage between this and the final, well-formed flange (Plate X, fig. B and figs. 16K and L).

Chemical Nature of Flanges.

Flanges are rather more acidic than body portions, according to the evidence from their specific gravity values. The average specific gravity value for a statistically significant number of individual flanges or flange fragments is 2·385, compared with a value of 2·426 for body portions. The difference (0·04) suggests compositional variation between the two, since the effects of small gas inclusions on the mean specific gravity values are of little significance, and since the specific gravity varies fundamentally with silica content. Compositional variation within one and the same flange is sometimes evidenced by colour banding and often by the existence of flow streaks. Darker coloured bands alternate with almost colourless bands in the chin regions of some flanges, but no such colour banding is ever observed in the body portions of australites. The darker colour of certain bands in some flanges is attributed to small degrees of oxidation of the ferrous iron content, a process that can only have developed during atmospheric flight.

THE CURVATURE OF TEKTITE SURFACES.

The arcs and radii of curvature of the surfaces of tektites have been principally investigated for australites (Baker, 1955a, 1955b, 1956), where a remarkable degree of geometrical symmetry has been attained and preserved in many forms, and where it is reasonably certain that the two surfaces investigated—one a primary remnant (posterior surface), the other a secondarily developed feature (anterior surface)—have not been excessively modified by terrestrial erosion.

Earlier references to the nature of the curvature of the two different surfaces of australites, have been made by Stelzner (1893) and Walcott (1898, p. 33). A hollow australite "sphere" which is not externally abraded, obtained from Kangaroo Island, South Australia (Plate XIV, fig. 1), sent to the "Bergakademie" at Freiberg, Saxony, was noted to consist of a hemisphere and a less curved, spherical surface, the two parts being connected concentrically (Stelzner, 1893). Button-shaped australites have both surfaces usually convex, the bottom (smaller) often being of greater convexity than the top (larger), and they were said to be like two hemispheres of unequal diameter joined together to form a more or less spherical body (Walcott, 1898, p. 33). A recent

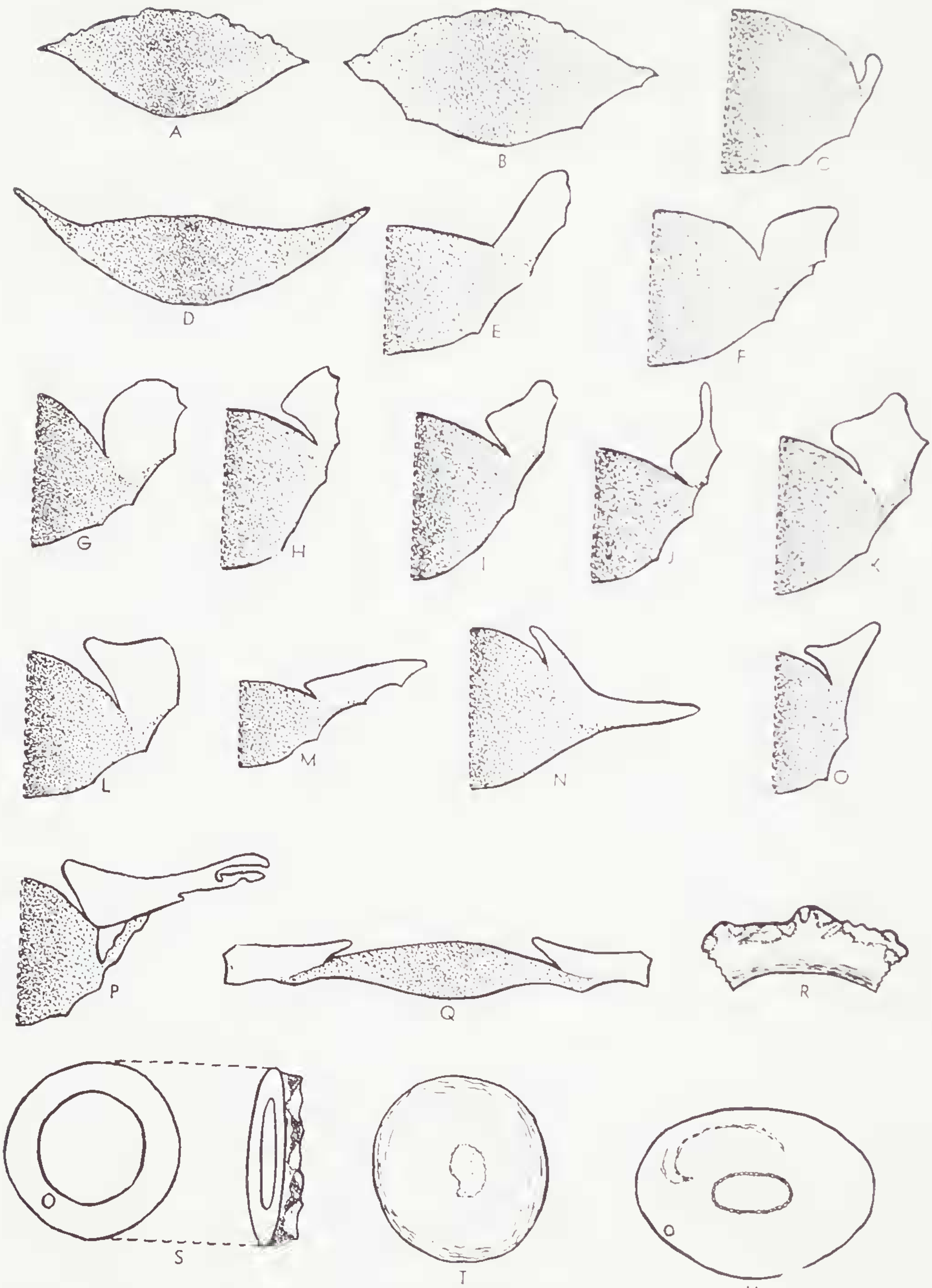

FIGURE 16.

FIGURE 16.—Diagrams illustrating shapes and positions of rims and flanges on australites (posterior surfaces uppermost).

A—lens with rim.
B—oval with equatorial projection of glass developed to a stage between that of rim and flange.
C—partially backward-curved, newly-formed flange on an oval.
D—flange-like rim, curved back at the drawn-out ends of a canoe-shaped form.
E—flange with smooth outer edge, arranged at 60° to the central body portion of a dumb-bell-shaped form.
F—flange with neck surface vertical; from a button-shaped form.
G—flange with convex posterior surface, from a button-shaped form.
H—flange showing neck recurved over posterior surface of a button-shaped form.
I—flange with well-marked chin and concave posterior surface, from a button-shaped form.
J—flange with concave posterior surface; marked chin and outer edge recurved towards posterior surface.
K—thick flange from button-shaped form. Chin and neck portions considerably overlap the posterior surface of the body. Topmost flow ridge on anterior surface developed into a conspicuous hump.
L—type of flange common on several well-developed button- and oval-shaped australites. Posterior surface of flange slightly concave and almost horizontal. Chin and outer edge rounded and smooth.
M—flange on almost flat-topped button, arising at 20° to the central body portion.
N—compound flange. Outer edge thin and drawn-out in a horizontal plane. Chin recurved over posterior surface of body.
O—compound flange with prominent chin recurved, outer edge portion nearly vertical.
P—compound flange with wide chin and flow-grooved outer edge deeply etched.
Q—cross section of disc-shaped form, showing narrow core and prominent flat, horizontal flange.
R—portion of flange with smooth inner edge and crenulate outer edge due to strongly developed wrinkling of flow ridges on the anterior surface (plan aspect).
S—plan and side aspect of a detached complete flange from a button-shaped form, showing narrow width of flange compared to diameter of interior portion from which the central body core has been removed. Chin region of flange smooth, with bubble pit on posterior surface.
T—equatorial section of a disc-shaped form; flange width in excess of diameter of central body portion. Core marked off from flange by a series of fine flow grooves.
U—posterior surface of an oval, plate-like form with fine flow lines and a bubble pit. Flange width greater than diameter of central body portion. Core marked off from flange by an elliptical arrangement of minute, oval-shaped bubble pits.

All specimens from Port Campbell, Victoria (after Baker, 1944).

detailed study of the arcs and radii of curvature of the two surfaces of australites, however, has shown that many of the button-shaped australites are, like the lenses, lenticular rather than spherical (Baker, 1955a, 1956).

Surface Curvature Relationships in Australites.

The curvature and relationships between arcs and radii of the curvature for posterior (RB) and anterior (RF) surfaces of 194 complete or nearly complete australites from Port Campbell, Victoria, Australia, have been determined by the author. Each specimen was adjusted on a mounting medium with its vertical axis (i.e., polar axis) parallel to a horizontal plane, and the silhouette of each traced from the image obtained on the viewing screen of a Panphot instrument. Depth diameter relationships and radii of curvature were determined from these tracings after re-adjusting the measurements according to the magnification used. Round forms (buttons, discs, lenses and large round cores) were always mounted in two positions at right angles to ascertain any variations in surface curvature; they showed very little departure from constant curvature in each direction, and this was principally due to minor irregularities such as flow ridges on anterior surfaces and bubble pits on posterior surfaces. These were smoothed out in the tracings as they did not intrinsically affect the surface curvatures as a whole. Elongated forms (ovals, boats, canoes, elongated cores, dumb-bells and teardrops) showed different curvatures for the two positions at right angles. The centres of constructed circles for each specimen were obtained by drawing three chords for each curved surface, and bisecting these at right angles. Three point intersections were obtained in the majority, a few had a small triangle of error. The round forms, the smaller cross sections through elongated forms and very few of the longer sections through elongated forms, fitted the arcs of constructed circles.

Slight departures from regularity in some equatorial zones of anterior surfaces, arose because the curvature of some flanges is a little less convex than that of the related body portion. On the whole, however, very few of the arcs of curvature of the two surfaces — posterior and anterior — showed departures from concordance with the arcs of constructed circles, for the australites that are round in plan aspect. This indicates that the posterior surfaces, which are remnant surfaces, represent portion of an original sphere or a spheroid very closely shaped like a sphere. It also shows that australites generally maintained a stable position during atmospheric flight, since their secondarily developed anterior surfaces preserved a regularly curved character. As a generality, it has been observed that forms with greater RB values also have greater RF values, and that some forms with flatter posterior surfaces invariably possess steeper curvatures on anterior surfaces (i.e., smaller RF values). In discs, an ultimate stage was reached in which RB attained infinite radius of curvature (i.e., the posterior surface is flat) and the RF was large for the size of the specimen. With the passage of discs into bowl-shaped forms, RB becomes negative in sense, the curvature of the back surface being directed in the same way as the front surface, but is usually of greater radius.

Certain round forms (predominant among australites) were found to have the same RB for varying RF. The relationships of eight such forms, each with RB = 10 mm., are illustrated in fig. 17. Their posterior surfaces (regarded as remnants of primary surfaces) have the same radius of curvature. In each, the surface curvature is maintained as a regular curvature from the back pole to the equatorial periphery for all silhouettes obtained by rotation about the polar axis. The curvature for each surface closely corresponded with that of the arc of a constructed circle.

These eight forms evidently started their journey earthwards as spheres of similar size, but by secondary fusion and ablation during the atmospheric phase of flight, varying amounts of glass were regularly removed. The curvature of each anterior surface corresponded to the arcs of curvature of constructed circles possessing different radii, and the depths of the ultimate secondary forms vary according to the positions of intersection of the anterior and posterior surfaces in each form. Since forms with the same R_B are under consideration, the variation in depth is largely a function of variability in R_F.

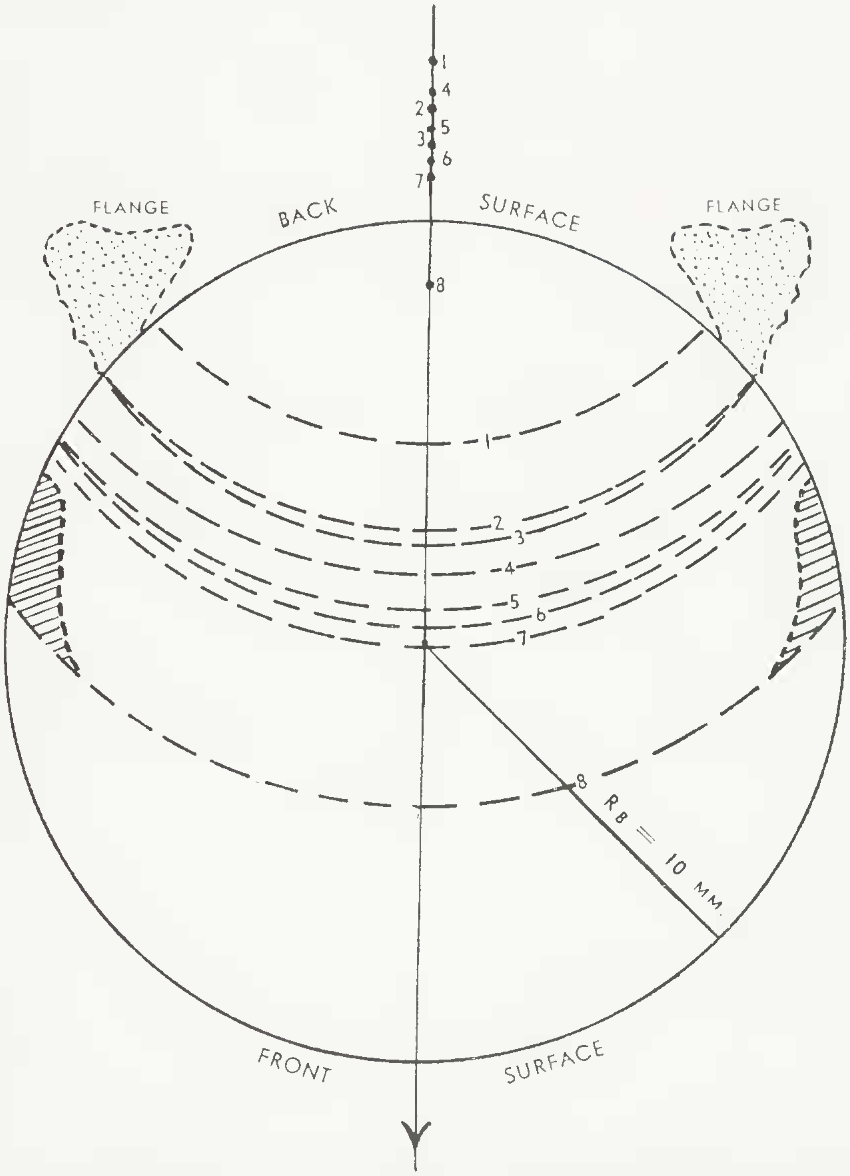

FIGURE 17.—Relationships of the curvature of australite surfaces. Several forms with the same curvature of back surfaces ($R_B = 10$ mm.) have varying curvatures of front surfaces. Numbers indicate centres and arcs of corresponding curvatures ($\times 5$).

These results are in accord with Fenner's (1938b, p. 204) ideas, and show that deeper forms never developed flanges and were subjected to equatorial flaking. The optimum position for flange formation was reached when

approximately 60 per cent. or more of the original sphere had been lost by ablation and/or flaking. In the series illustrated in fig. 17, a flange did not form until R_F had reached a value of approximately 11·5 mm., a conclusion supported by the examination of many specimens of australites that are round in plan aspect. Shaded areas in fig. 17 represent positions from which glass was lost by equatorial flaking and ablation, in a form that had reached a stage when R_F was 12·5 mm. Stippled areas represent glass collected in equatorial regions as a flange structure at a stage when R_F was 9·5 mm. With various stages in loss of material, there was accompanying reduction in radius of curvature of the anterior surface. With R_F at 12·5 mm. (fig. 17, No. 8), at least a third of the original sphere had been removed. With R_F at 11 to 11·5 mm., one half and over was lost, and with R_F at 9 mm., at least two-thirds of the original sphere was lost.

Similar relationships can be obtained by commencing with sets of spheres with greater original radii of curvature, so that spheres of australite glass of the same original size, attain various final sizes of the secondary forms by differential loss of glass from front surfaces. This loss occurred in a more or less regularly progressive manner. The following diameters are those of original spheres from which round forms of australites were derived (Fenner, 1938):

(1) bung type .. .. 47 mm.
(2) core type .. .. 31 mm.
(3) button type .. .. 16 mm.
(4) large lens type .. .. 17 mm.
(5) small lens type .. .. 10 mm.

The greatest R_B value for the australites whose radius of curvature was determined herein, was 18·6 mm. for round forms and 33·2 mm. for an elongated (boat-shaped) form, showing that the largest original sphere in this series was 37·2 mm. in diameter, and the largest original ellipsoidal form was approximately 66·5 mm. in length. The maximum value arrived at for the diameter of original spheres of australite glass, is 5·5 cms. (Fenner, 1938), but the minimum diameter is uncertain, as no microscopic australites have yet been recorded. The smallest among 1,500 australites from Port Campbell, Victoria, was originally 4 mm. in diameter. The size relationships of the eight forms indicated in fig. 17 are shown in Table 10.

TABLE 10.

No. in Fig. 17.	Depth in mm.	Diameter of Ultimate Form in mm.	R_F in mm.	R_B in mm.
1	5·4	13·0	9·0	10
2	7·4	15·5	10·0	10
3	7·8	15·5	9·5	10
4	8·4	17·0	11·5	10
5	9·2	17·6	11·5	10
6	9·8	17·8	11·0	10
7	10·0	18·1	11·5	10
8	14·0	19·4	12·5	10

Each form included in Table 10, was originally a sphere of 2·0 cms. diameter. Although $R_F = R_B = 10$ mm. in specimen 2, the ultimate secondary form is not spherical because the centres for the two radii of curvature are not coincident, and the two constructed circles about these curvatures are coaxal circles.

The nature of ultimate secondary forms produced and the stages passed through in australite development are indicated from a study such as this, which leads to the observation that (i) despite the general trends shown in fig. 17, some forms are slightly deeper than others with the same RB, because centres of curvature for RF are differently located on the polar axis, and (ii) there does exist a series of different stages (Nos. 1 to 8 above) in the production of different sized secondary end shapes from original spheres of the same size.

Measurement of the radii of curvature of a number of primary remnant surfaces of the round forms of australites, indicates that there existed primary spheres of different original diameter. The production of secondary shapes of different size during atmospheric flight earthwards, was evidently controlled in some measure by (i) variations in distance travelled by the individual spheres, or (ii) variations in their velocity, or (iii) probable variations in density of the atmosphere, as well as by the size of the original spheres when they originally entered the atmosphere as cold bodies.

In a series of round australites with the same radius of curvature of the front surface (RF) for only slightly varying depth values, the radii of curvature of the posterior (i.e., primary) surfaces vary. Similar end stages of ablation were thus reached on spheres of different original size. The spheres in two separate series investigated, varied (i) from 7 to 8·5 mm. RB for a constant RF of 8·5 mm., and (ii) from 9 to 11 mm. RB for a constant RF of 11·5 mm.

Increased radii of curvature of front surfaces also resulted on forms with greater radii of curvature of the rear surfaces, although small discrepancies were evident in a few specimens. The relationships between the two separate radii of curvature, and between these factors and depth and diameter measurements, have been indicated in detail by means of frequency polygons and scatter diagrams for the Nirranda Strewnfield australites, Victoria (Baker, 1956) the Port Campbell australites (Baker, 1955a), and the Harrow australites, Victoria (Baker, 1955b).

Ranges in the radii of curvature of back (posterior) and front (anterior) surfaces of a number of Port Campbell australites are listed in Table 11.

TABLE 11.

	Posterior Surface.	Anterior Surface.
Button-shaped forms—		
RB > RF	7·0 to 12·7 mm.	5·4 to 12·4 mm.
RB < RF	4·7 to 14·1 mm.	5·3 to 14·9 mm.
Lens-shaped forms—		
RB > RF	6·5 to 10·5 mm.	5·1 to 9·5 mm.
RB < RF	4·9 to 9·3 mm.	7·0 to 11·3 mm.
Oval-shaped forms—		
RB > RF	6·7 to 24·0 mm.	6·1 to 15·7 mm.
RB < RF	4·6 to 13·6 mm.	5·6 to 15·0 mm.
Boat-shaped forms—		
RB > RF—		
Short diameter	6·0 to 14·2 mm.	4·1 to 9·0 mm.
Long diameter	12·0 to 33·2 mm.	11·0 to 23·0 mm.
RB < RF—		
Short diameter	6·1 to 10·3 mm.	7·5 to 11·0 mm.
Long diameter	10·0 to 22·4 mm.	12·0 to 22·9 mm.

Button-shaped specimens with R_B less than R_F are dominant, there being 88 per cent. of such specimens. Forms with R_B greater than R_F have flatter rear surfaces and ultimately grade into thin, disc-shaped australites which have more or less flat rear surfaces; 84 per cent. of the lenses have R_F greater than R_B, and so have 50 per cent. of the oval-shaped and 27 per cent. of the boat-shaped forms. All of the cores (six specimens only) had R_B greater than R_F.

In plan, round australites (including flanged forms) almost completely accord with geometrically constructed circles, with only minor irregularities.

The study of the nature of the curvature of back and front surfaces of australites, shows that very few round forms provide indications of departures of their original sphere-like bodies from true sphericity, many attaining almost geometrical perfection. The surface curvatures of both long and short diameters of several elongated forms of australites, both conform with the arcs of curvature of constructed circles. This applies more particularly to oval-shaped forms that are not far removed from button-shaped australites. In the more elongated examples such as boats, canoes, &c., it is only the curvature across the short diameter that conforms to the arc of curvature of a constructed circle, the curvature along the longer diameter being usually flatter in the front polar regions and steeper towards the equatorial edge. In other words, such forms were evidently derived from original ellipsoids of revolution.

The radii of curvature for the long and short diameters of ovals are only slightly different in amount.

The degree of perfection maintained by the curvature of posterior (primary) surfaces of australites, points to the round forms having been generated from original well-developed spheres of glass. The attainment of an almost hemispherical character by many anterior (secondarily developed) surfaces, indicates that equilibrium of position was maintained during atmospheric flight. Had the objects developed a marked wobble, the symmetry of curvature of the front surface would probably not have been preserved. Rare examples do possess a rather skew curvature of anterior compared to their relationships with the associated posterior surface. Such is detected in silhouette tracings of the forms, by centres of curvature of these particular anterior surfaces not falling on a line that is perpendicular to the diameter of the form, and at the same time parallel to the direction of propagation. On the other hand, centres of curvature for the posterior surfaces are always located on this perpendicular. This suggests the development of a slight wobble during flight. In general, centres of curvature for both back and front surfaces are located on the polar axis of the more symmetrical objects, and this axis was thus parallel to the direction of propagation. The polar axis corresponds with the true depth (or thickness) of australites, and is at right angles to the diameter line, which corresponds in graphical constructions with the radical line that joins the points of intersection of two coaxal circles in which the two centres are collinear.

Figure 18 shows silhouette traces of several forms of australites around which constructed circles closely fit the curvatures of both surfaces over their major portions. In many of these forms, however, the arc of curvature of each surface seldom occupies more than 30 per cent. to 35 per cent. of the arc of curvature of the constructed circle.

Where forms possess both longer and shorter diameters (e.g., oval- and canoe-shaped forms), the nature of the curvature is indicated in fig. 18 for each surface in two positions at right angles.

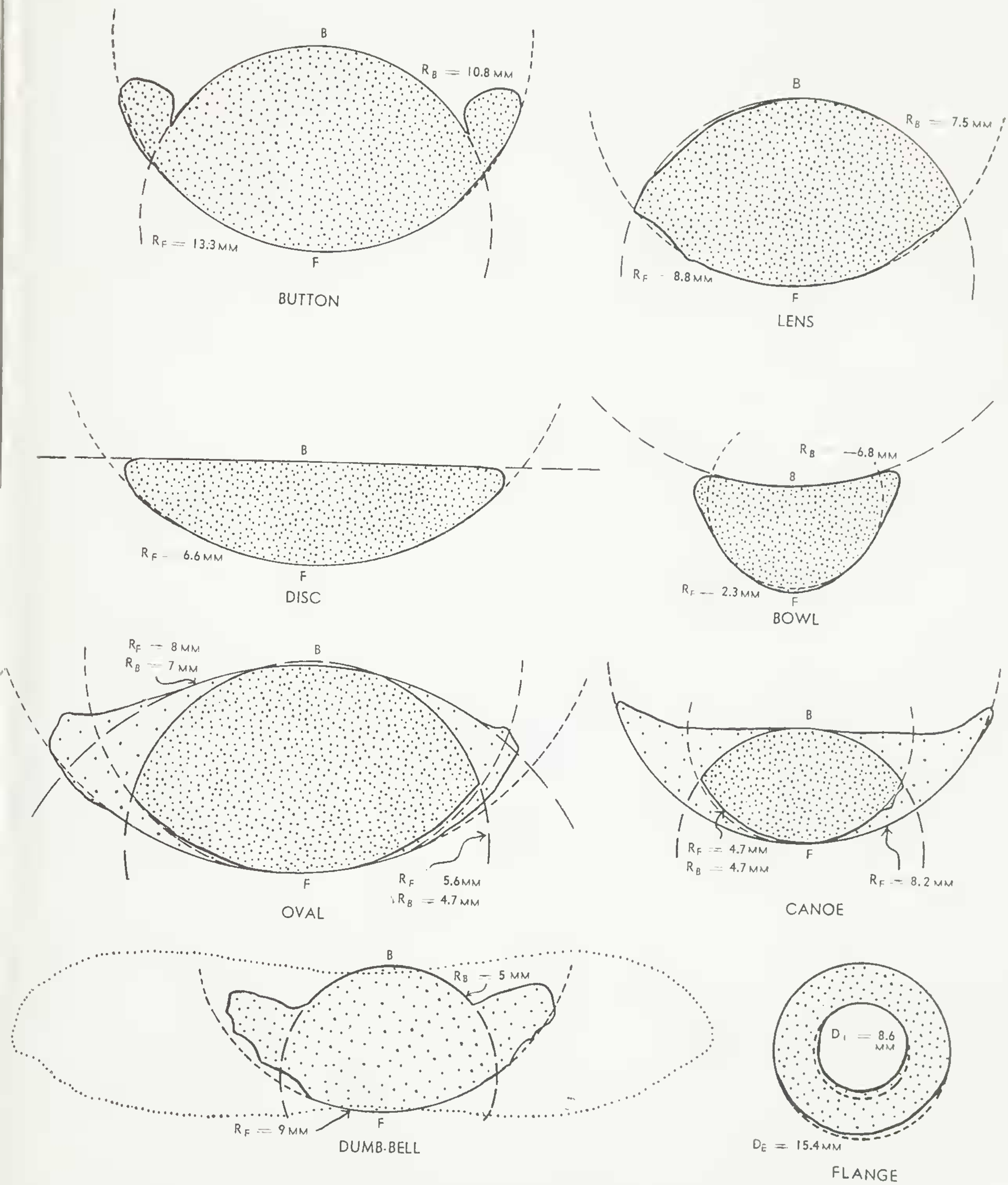

FIGURE 18.—Curvatures of anterior and posterior surfaces of the various forms of australites. Curvatures are congruous with the arcs of constructed circles. B = back surface, F = front surface, R_F and R_B = radii of curvature of front and back surfaces, D_E and D_I = external and internal diameters.

The relationship of the R_F and R_B values is shown in the scatter diagram fig. 19 for 76 button- and 32 lens-shaped australites from Port Campbell, Victoria.

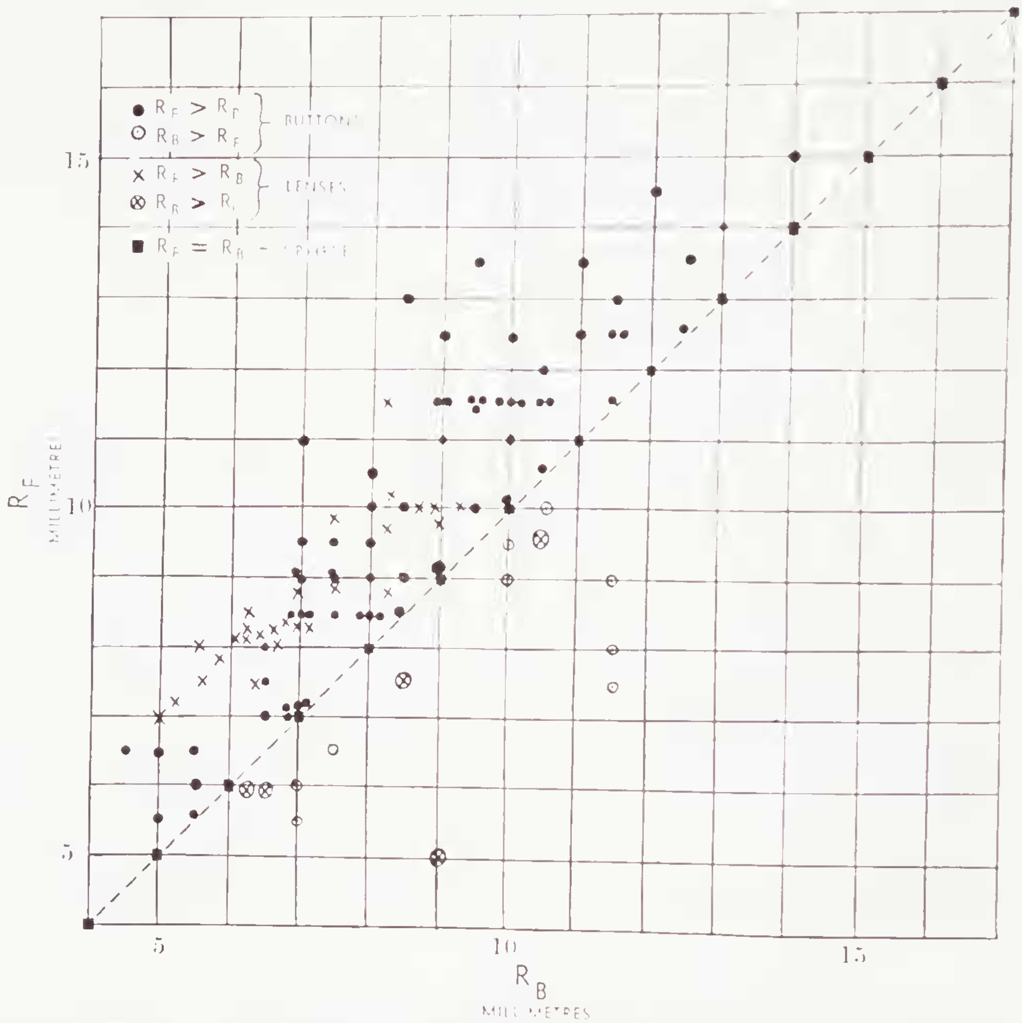

FIGURE 19.—Scatter diagram showing relationship of radius of curvature of back (R_B) and front (R_F) surfaces of button- and lens-shaped australites.

Most buttons and lenses fall above the straight-line-relationships (unit gradient) for true spheres, and they occur in the region where R_F is greater than R_B. Clusters near unit gradient, represent forms in which R_F and R_B are similar in magnitude, but these are not necessarily spherical forms, since an approach to sphericity depends upon the distance apart of centres of curvature for each surface. Such forms are still lenticular in cross-section, since their silhouette tracings are those of two intersecting coaxal circles. The scatter diagram (fig. 19) reveals the tendency for R_F to increase with larger values of R_B, while certain forms with the same R_B, have different R_F values, and vice versa.

When the mass of the various spheres of calculated original R_B is determined for australite glass, using an average specific gravity of 2·40, and the results graphed, the relationship obtained is that indicated by the curve on the left in fig. 20.

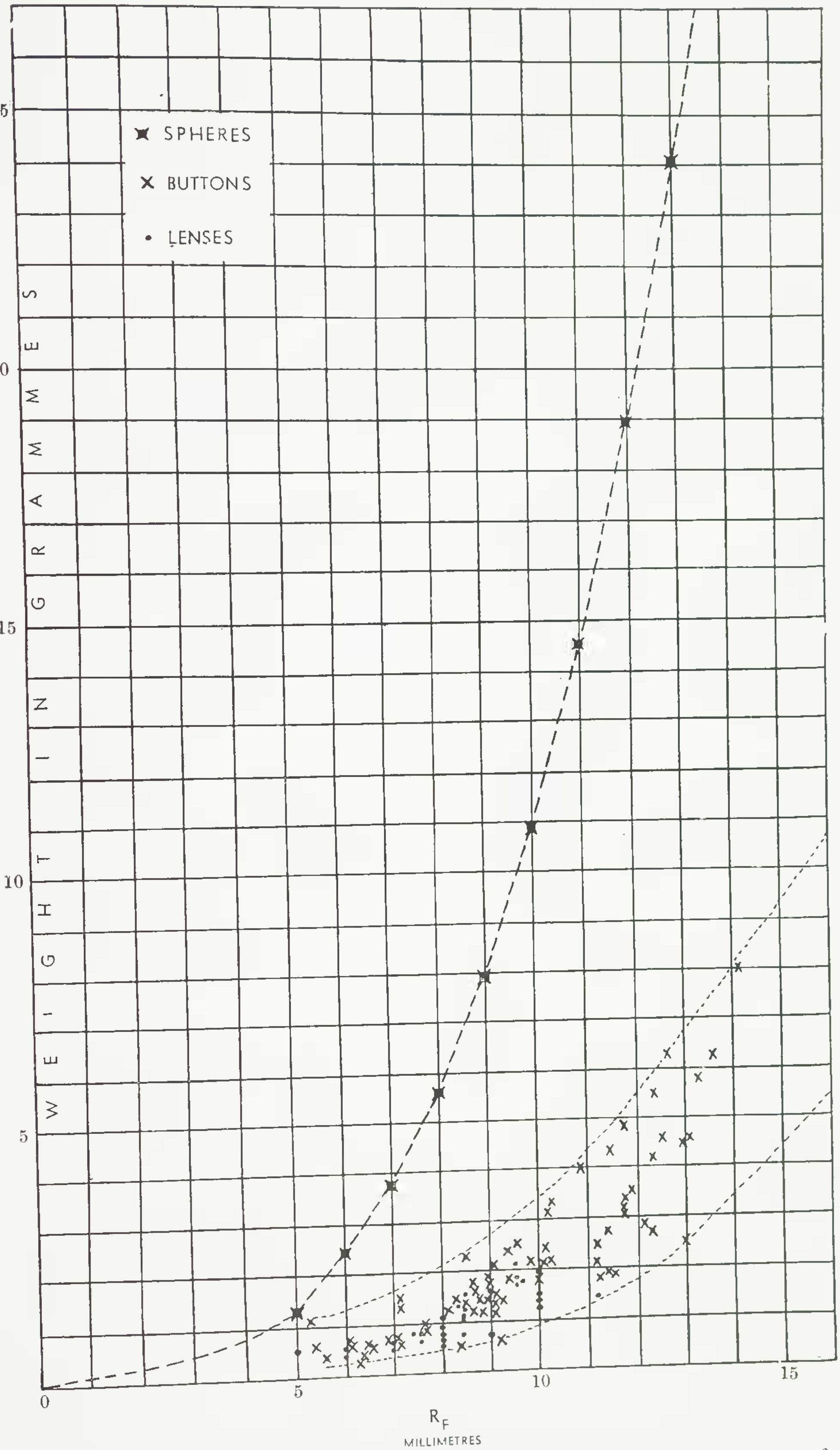

FIGURE 20.—Graph illustrating relationship between mass and curvature of front surfaces of button- and lens-shaped australites.

Radius of curvature of front surface increases with weight (i.e., increased size), and it can be deduced that the smaller original spheres of australite glass lost proportionately less material than the larger original spheres. Buttons of about 5 grams weight were derived from spheres originally weighing approximately 21 grams; buttons and lenses of 1 to 2 grams from spheres of 5·5 to 11 grams. Depth of the forms would affect their positions on the graph (fig. 20) to some extent, but not enough to nullify the generalizations.

Internal and External Curvatures of Hollow Australites.

A tracing of the outer and inner surfaces from Dunn's illustrations (1908, plate 33 and 1912b, plate 7) of a hollow australite found at Hamilton, Victoria, shows that the exterior of the back surface conforms with the curvature of a circle of radius 29 mm. (fig. 21). The front surface is also coincident with part of the arc of a constructed circle, but of rather smaller magnitude (26·5 mm.). The form was originally spherical externally.

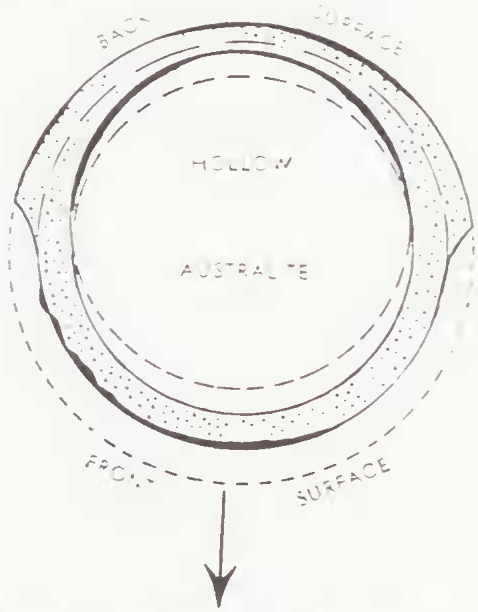

FIGURE 21. Diagram of hollow australite showing relationship of curvatures of inner and outer walls of posterior and anterior surfaces. Thickened dark areas indicate positions where the surfaces do not quite coincide in curvature with the arcs of constructed circles.

Little glass was lost by ablation from the front surface, a thickness of 5 mm. having been removed from the front polar regions and 4 mm. from the equatorial regions. Although the curvatures of the internal walls of back and front surfaces conform with constructed circles, and have the same radius of curvature (21 mm.), the centres of the two circles are not coincident, and the two curvatures intersect in the equatorial regions of the form. The bubble is thus elliptical, though departing but slightly from a spherical shape. It corresponds in shape with that of a biaxial ellipsoid 44·5 mm. long and 42 mm. wide. The elongation of the bubble is in the same direction as that assumed by the object during flight (direction of arrow in fig. 21), thus conforming to the known facts relating to streamlining phenomena. Elongation occurred outside the earth's

atmosphere, because only in the early stages of formation would the glass walls, particularly rear surface walls, be plastic enough to distend. Most distortion was taken up by the inner wall of the back surface, because at the back pole, the glass is 1·25 mm. thinner than at the front pole. Account must also be taken of the fact that the front pole lost a thickness of 5 mm. by ablation subsequently during atmospheric flight, so that the real difference in thickness was originally greater, somewhere in the region of 6·25 mm. thicker. Had the bubble become distorted in a plastic object during flight through the atmosphere, i.e., during a phase of flight when the back surface was cold, distortion would be expected to have occurred by equatorial bulging, and not by the polar elongation shown by the bubble.

A rather larger hollow australite from Upper Regions Station, Horsham, Victoria (Walcott, 1898, plate III.), shows similar curvature relationships. The inner wall of the bubble has $R_B = 22$ mm. and $R_F = 22$ mm. The outer wall has $R_B = 31 \cdot 5$ mm. and $R_F = 28 \cdot 5$ mm. The four surfaces conform regularly to the arcs of constructed circles. The hollow australite from Horsham lost 7·5 mm. thickness of glass from the polar region of the front surface. It is slightly elliptical like the Hamilton hollow australite, the length being 47·5 mm. and the width 44·5 mm. Its direction of elongation is also parallel with the direction of propagation through the earth's atmosphere. As described by Walcott (1898), " the interior is slightly egg-shaped, the greatest diameter of 47·5 mm. being in the direction of the smallest outside diameter of 52·5 mm." The difference in thickness of the walls at the back and front poles respectively is 2 mm., the walls being 3 mm. thick at the back and 5 mm. at the front pole. (This specimen, of 1·05 specific gravity, was sliced, but the included gas was not collected).

With the above information and other detailed relationships between the arcs and radii of curvature (Baker, 1956, 1955a, 1955b) of posterior and anterior surfaces of australites now available, a basis is provided for the development of more modern theories to explain the origin and relationship of the limited number of the secondary shapes possessed by australites (see Chapter X).

CHAPTER V.

THE INTERNAL STRUCTURES OF TEKTITES.

Flow Structures—Inclusions—Gas Content.

FLOW STRUCTURES.

The marked flow structure patterns of tektites are characterized by "schlieren" with slightly different chemical compositions.

The streaky nature of javaites from Solo, Central Java, has been noted in thin splinters (Heide, 1939). In the crystal-bearing (?)tektite from Paucartambo, Peru, the streaky nature is manifest only in the fluidal disposition of the crystalline fraction, but in other tektites, streakiness is due to slightly variable composition between individual schlieren.

Well-marked flow structures, likened to "arrested heat waves" in bediasites, are much contorted and unrelated to external surfaces (Barnes, 1940a, p. 503). Bands of anisotropism in bediasites correspond with flow structures and are due to strain. Strained areas are irregularly distributed, varying with alternation of tensional and compressional zones.

Flow structure in tektites is due essentially to some small measure of inhomogeneity of the glass, strain effects resulting from differences in the coefficient of expansion of various parts, followed by cooling before the glass became completely homogeneous in composition. The flow structure is made visible by differences in the refractive indices of adjacent streaks of glass of different composition. The shape of the flow structure in any bediasite has been considered useful as a guide to the amount of material subsequently removed by corrasion and corrosion, since the flow structures in some specimens are sharply truncated, as if they had at one time continued much farther (Barnes, 1940a).

In sections of some of the French Indo-China tektites, flow structures have been observed to parallel the surfaces of some specimens, while moldavites show sharp truncations of the flow structures as in bediasites. Where flow structures within tektites are much contorted, it would appear that disturbances have been brought about by some such factor as the escape of abundant gas. Added to this are the effects of compressional and tensional strains set up during the extraterrestrial initiation of each tektite as an independent body, and subsequent strains and stresses set up during rapid atmospheric flight earthwards. In this respect, it has been calculated by means of retardation measurements (Hammond, 1950, p. 272) that some strain lines in moldavites are under compressive stresses of 1,220 lb. per square inch, others are in tension with a stress of 735 lb. per square inch. In some moldavites, however, no regions of the glass show greater strain stresses than 25 lb. per square inch.

In indochinites, birefringent areas due to strain and areas of tension or compression have been observed around microscopic bubbles (Lacroix, 1932), as in other tektites also.

The internal flow structures of tektites have, in the past, been compared with those in obsidian of terrestrial origin, but the obsidians only resemble tektites in the coarser etching structures, being free of the fine flow lines present in tektites (Barnes, 1940a). Moreover, such flow structures in obsidian are only plainly evident in more weathered portions, whereas in the youngest and best preserved of the tektites, namely australites, the flow structures are especially well-marked inside any sectioned specimen (Plates X, XI, and XII).

Thin sections of australites have been examined by few workers on this subject, and it was only with improvements in microscope and photographic techniques that their complexity and significance became recognized. In 1896, Moulden noted that when the glass of the Australian "obsidian bombs" was sliced through, it showed a compact interior, with merely one or two "steam-holes" or cavities. Vertical and horizontal sections through australites examined by A. W. Howitt (see Walcott, 1898), showed "a number of cloudy, narrow, more or less contorted bands at places closely intermingling". Both A. W. Howitt and E. G. Hogg (see Walcott, 1898, p. 31) expressed the opinion that the slight birefringence shown under crossed nicols was due to strain caused by rapid cooling. Several thin slices of australites showing internal flow structures were later illustrated by Dunn (1912b, Plates 10 to 17). The photographs, taken by transmitted polarized light, shed a flood of light on the flow structures in these tektites, especially in the relationships of flanges to cores. From the flow pattern revealed, Dunn deduced that the central core formed first by means of the flowing down of glass inside a highly fluid bubble and the confused flow structure was adjudged to result from rapid downward flow of superfluous material from the upper portions of the bubble. Although now regarded as essentially incorrect, Dunn's ideas nevertheless provided a basis for further investigations. Improved techniques in representing the complicated internal flow structures of australites, and the assistance derived therefrom in their interpretation wherever possible, has led to fairly satisfactory proof that the glass composing australite flanges was secondarily derived from the sheet fusion of the polar regions of anterior surfaces and the migration of glass so formed towards equatorial regions (Baker, 1944).

Occasional internal cracks in australites (Plate XI, fig. A) result from strains set up during cooling and they were subsequently opened out during atmospheric weathering. They transect internal flow lines without displacing them, and are themselves sometimes interrupted without offsetting by internal gas cavities.

The flow lines in australites (Plates X to XII) are mostly drawn-out streaks of glass of slightly varying chemical and physical constitution. Those leading to the bases of bubble pits on external surfaces (Plate XI, figs. C and E) represent directions of gas streaming. Many of the flow streaks show refractive index variations and strain polarization effects. Drawn-out, resorbed particles of lechatelierite have contributed considerably to these variations. Some flow lines open out into tubes on the external surfaces, thus forming channels of varying depth, and referred to as flow grooves, channels, gutters, bubble tracks, &c., which sometimes become overdeepened by processes of natural etching.

Directions of glass streaming are readily determined in flanges of australites (Plate XII), but the flow patterns in most body portions are extremely complex (Plates X and XI) and evidently arose during the initial extraterrestrial formation of independent tektite bodies. In the flanges, which are of secondary development, spiral and elliptical flow lines indicate turning over of australite glass forced from fused films of anterior surfaces of body portions. Jamming of warmer and later introduced glass against cooling or already virtually cooled glass accumulated in equatorial regions of the forms led to complex puckering of flow structures in many of the flanges (Plate XII, fig. A). The major flow-line trends in body portions are sometimes partially towards (Plate XI, fig. E) or along (Plate XI, fig. D) posterior surfaces, but they sometimes show a crude radial structure from the centre outwards to both surfaces. These are evidently primary flow structures. Along anterior surfaces, flow-line trends near the outer surface are frequently well marked and lead towards the equatorial zones where the flanges develop (Plate X, fig. B).

The truncation of flow lines in "flow wave" structures in the equatorial regions of anterior surfaces (Plate XII) indicates loss of australite glass by ablation and/or fusion stripping during the end stages of flight.

Lines of union between flanges and body portions (i.e., attached cores) in thin sections of australites are observed to be usually marked by sharp dark lines separating regularly flow-lined flanges from bubble-pitted, irregularly flow-lined equatorial regions of body portions. Small bubble cavities are often assembled near lines of union and occasionally form part of them; they and the lines of union are arranged contiguously with arcs of curvature of posterior surfaces of body portions. Before reaching anterior surfaces, lines of union usually swing round sharply to continue parallel with anterior surfaces for a short distance. They ultimately pass out into the flanges as flow lines (Plate XII), and mark off narrow, shelf-like portions referred to as the "seat". The flanges present the appearance of being supported upon the "seat" structures, which are the same as structures regarded by Dunn (1912) as being where glass bubbles joined the cores of blebs prior to flange formation. Where lines of union pass rapidly out towards anterior surfaces (Plate XI, fig. A), the "seat" structure is reduced in length or sometimes entirely wanting, due to advanced processes of ablation in these regions, and the thickness of glass between the base of the "seat" structure and the anterior surface varies up to 6 mm. Reduction in the thickness of the glass in these positions favours ready detachment of flanges, both during atmospheric flight and/or subsequently by weathering.

INCLUSIONS IN TEKTITES.

Early observers noted few inclusions in tektite glass. Those in javaites from Solo, Central Java (Heide, 1934), in indochinites from the Far East (Lacroix, 1932), and in the Ivory Coast tektites (Lacroix, 1934), were all pronounced as being small gas bubbles. Small rods and drawn-out inclusions have been observed in the billitonites by Verbeek (1897), Suess (1900) and by Dittler (1933), and also in the Borneo tektites by Mueller (1915). "Glass enclosures" referred to in moldavites by Rutley (1885), and in both the australites and Bohemian tektites by Suess (1900), are most likely the same as inclusions now referred to as lechatelierite particles (Barnes, 1940a, Baker, 1944).

Lechatelierite Particles in Tektites.

Lechatelierite particles in tektites are minute in size, and mainly only visible under the highest powers of the petrological microscope. They represent re-fused quartz. In bediasites they have been observed to vary in size from 0·015 mm. to 0·48 mm., and average 0·136 by 0·032 mm. The number per cc. in one bediasite has been estimated as 690, and the per cent. by volume as 0·0048. Another bediasite had 25 times as much volume as this occupied by lechatelierite particles (Barnes, 1940a, p. 504). Wide variations in shape of the lechatelierite particles occur in both bediasites (Plate VII) and moldavites. Distortion and elongation into ribbon-like bodies along flow directions are due to turbulency created during the development of flow structures.

The presence of lechatelierite particles in tektite glass indicates limited liquid miscibility, for if the original material contained quartz grains or other non-hydrous silica before it was melted, and if fusion was rapid followed by rapid cooling, the quartz would fuse to lechatelierite. Because of its viscosity, it would not thoroughly mix with the rest of the glass in the time available.

The presence of lechatelierite particles in tektite glass has been taken to represent a state of liquid immiscibility in a silicate melt (Cassidy and Segnit, 1955).

Lechatelierite particles are also recorded from (i) glass formed by a broken power line arcing through the soil on which it fell, (ii) glass formed by fusion of a non-calcareous shale, (iii) glass from artificially fused volcanic ash, and (iv) glassy material (re-fused in a carbon arc) formed about a burning and cratered petroleum and gas well. As in tektites, small bubbles of gas are often associated with the lechatelierite particles (Barnes, 1940a, p. 511).

Lechatelierite also forms the glass of *fulgurites* and the fused sandstone from the meteor crater of Canyon Diablo, Arizona. Particles resembling lechatelierite can be observed in some acid volcanic glasses.

As observed in australites and in a moldavite from Budweis, Czechoslovakia, the included lechatelierite particles are pale pinkish when embedded in the host glass, but colourless where protruding from the edges of crushed fragments. The pale pinkish cast results from absorption of light at the junctions of the particles and the containing glass, and is only visible under lower powers of the petrological microscope. In australites (Baker, 1944), lechatelierite particles are principally associated with more disturbed zones of the flow structures in flanges, where they lie along narrow, tube-like areas of glass with slightly higher

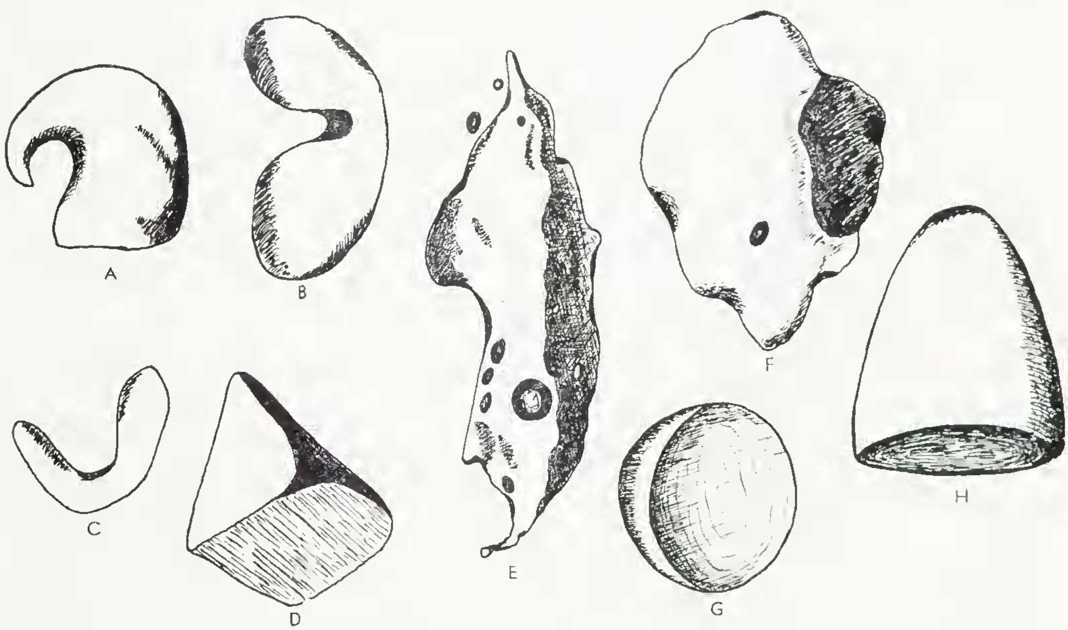

FIGURE 22.—Lechatelierite particles in australites.
A—hooked particle, length = 0·05 mm.
B—bean-shaped particle, length = 0·05 mm.
C—curled particle, length = 0·04 mm.
D—facetted particle, width = 0·04 mm.
E—irregular, flint-shaped particle with associated bubbles, length = 0·3 mm.
F—irregularly-shaped particle with included gas bubble, length = 0·07 mm.
G—hemispherical particle with flat base, situated in equatorial section of an australite flange, diameter = 0·03 mm.
H—elliptical, dome-like particle with flattened base, from australite core portion, length = 0·05 mm.
(Unless otherwise stated, included particles were observed in cross (radial) sections of australite flanges.) (After Baker, 1944.)

refractive index values than the more normal glass. They are common along lines of union between flanges and central body portions nearer the "seat" regions, but are rare in the less flow-lined area of flanges and even less frequent in the main portions, the core regions, of australites. The lechatelierite particles are of various shapes in australites, some are rounded, others irregular, facetted, hemispherical, bleb-like or granule-like (fig. 22, A to H).

Some of the particles are elongated, thread-like, ribbon-like, coiled, twisted and much contorted (fig. 23, A to G). The elongated particles are drawn out along flow-line trends in flanges, but not in the body portions. Their complicated puckering into contorted shapes in places substantiates Barnes's suggestion that similarly contorted lechatelierite particles in bediasites and moldavites result from jamming or turbulency. In australite flanges, the contortion of the drawn-out particles has been produced by jamming during the movement of warm against cooler glass in posterior regions of the flanges, and not due to turbulency so much. The small gas bubbles associated with the lechatelierite particles were evidently released during alteration of the original material (quartz or other non-hydrous silica) after which the lechatelierite particles are pseudomorphous.

Hemispherical particles (fig. 22, G and H) are localized to lines of union, and have their flat bases lying along the contact, and their hemispherical surfaces directed into the core.

Most lechatelierite particles in tektites are isotropic. A few slightly affect polarized light, indicating incomplete transition to lechatelierite. The irregularly-shaped particles (fig. 22, E) show low order grey polarization colours at times, and this, taken in conjunction with their irregular shape, suggests origin from broken, small quartz particles. They sometimes have a surrounding halo of pale coloured to colourless glass of refractive index intermediate between that of the included particle and that of the host glass.

The presence of lechatelierite particles in tektites suggests a means of solving tektite origin. It is reasonable to assume they could be remnants of incompletely resorbed quartz-bearing material from which tektites were developed. It can also be assumed, however, that they represent products of an earlier period of crystallization than tektite formation, that they had been re-fused during a subsequent stage of development, and passed into the hyaline condition, as suggested by Barnes (1940a). Their very presence does not elucidate the method whereby the original substance was heated to temperatures at which transition to glass occurred, because similar particles, although not usually as contorted or twisted, have been noted in Darwin Glass (due to natural smouldering of silica-bearing peat-bog material), Henbury Glass (due to meteoritic splash), artificial glass (fused sandy clay) and fulgurite glass (sand fused by lightning). The nature of the lechatelierite particles in australites precludes any suggestion that they may be foreign bodies picked up during flight, for under such circumstances various stages of alteration from partially changed original foreign material to lechatelierite would be expected. Moreover, it is extremely doubtful whether such hypothecated minute foreign bodies would be sufficiently concentrated to provide the abundant lechatelierite inclusions in australites, and none are ever found as partially unaltered material fused to external surfaces.

Whether they had an extraterrestrial or a terrestrial mode of origin is a controversial question. Barnes (1940b) considers their presence probably excludes a meteoritic origin for tektite glass, but there is nothing to disprove that they could have been developed upon some extraterrestrial source.

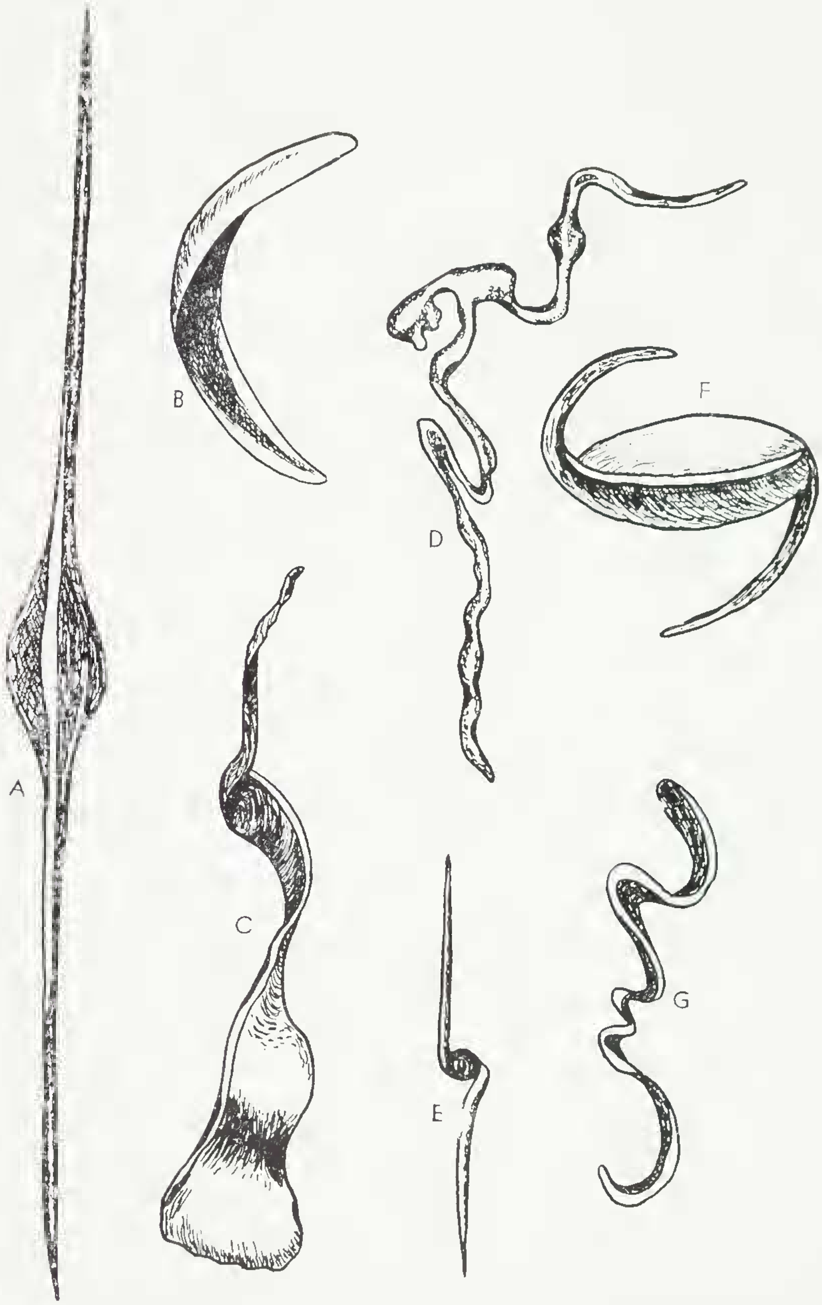

FIGURE 23.—Stretched and twisted lechatelierite particles in flow structures of australite flanges.

A—particle with flange-like process and drawn-out at the ends, length = 0·6 mm.
B—wisp-like particle, partially curled, length = 0·05 mm.
C—twisted, ribbon-like particle, length = 0·1 mm.
D—elongated particle, much twisted and contorted, length = 0·25 mm.
E—elongated particle showing one coil in central region, length = 0·25 mm.
F—lens-shaped particle with recurved, hook-like process, length = 0·07 mm.
G—twisted, elongated particle, length = 0·15 mm.

(After Baker, 1944.)

Inclusions in the Doubtful South American Tektites.

The Macusani, Peru, (?)tektites contain small crystals (Heide, 1936), and thus resemble the Paucartambo (?)tektite (Linck, 1926, 1928, 1934) in this respect. Although considered by several authorities as non-tektitic, Linck always maintained that the Paucartambo glass was definitely a tektite glass, and a crystal-bearing one at that (Linck, 1926a, p. 166), with a curious assemblage made up of both typical metamorphic and volcanic minerals (Plate XIII).

Linck recorded the following minerals in order of abundance: andalusite, sillimanite, wollastonite, scapolite, sanidine, oligoclase-andesine, zircon, aegerine-augite, basaltic augite, indefinite quartz, cordierite, spinel, cristobalite(?) and metallic granules. These occur as well-formed crystals, some as prisms and needle-like forms (Plate XIII), some arranged in the fluidal structure of the tektite glass. Glass drops up to 0·1 mm. across, of greater refractive index than the host glass, are associated with partially melted remnants of the minerals (Plate XIII, Nos. 19 to 21). Linck considered this mineral assemblage showed a remarkable paragenesis, never found in terrestrial volcanic rocks. The metamorphic and volcanic minerals are believed to have crystallized from the liquid glass and are not relics of a remelted rock.

GAS IN TEKTITES.

Virtually all the varieties of the tektites bear evidence of having originally contained gas, as indicated by their bubble-pitted surfaces. Most still contain small pores and a few contain larger cavities containing gas. Evidence of the prior existence of tektites with considerable gas cavities, the possession of which rendered them relatively unstable objects, comes from several sources, and mostly indicates that the contained gas was probably under negative pressures. Thus large hollow forms are indicated among moldavites from the presence of abundant fragments broken away from glass bubbles (Kaspar, 1938). Similar fragments of hollow forms occur among the australites, while some half a dozen or so known hollow australites in their complete forms, range in size up to 2 inches across. One such from Kangaroo Island (Plate XIV, figs. 1a and 1b) was regarded by Stelzner (1893) as reminiscent of the glass balls of black pumice observed by von Buch (1809, p. 51); this form floated in water and was faintly translucent when held up to the light.

Two other australites with large internal bubbles have been found at Hamilton in Western Victoria and at Charlotte Waters in Central Australia (Dunn, 1912b, plate 7). The inner walls of these hollow australites have a brilliantly polished appearance (Plate XIV, fig. 2) referred to as "hot polish", and the one from Charlotte Waters consists of two partially coalesced bubbles separated by the remnants of a thin septum of glass (Plate XIV, fig. 2); this phenomenon has not been noticed elsewhere among the tektites.

Australites with smaller gas bubbles ranging from 2 to 10 mm. across and thus less than a quarter the size of the hollow spherical australites, are known from Mulka in Central Australia (Baker and Forster, 1943, p. 386). Others of intermediate size have been found as rare members among australites from Port Campbell and the Nirranda Strewnfield in Western Victoria (Baker, 1956).

From Kelantan, Malaya, a large indomalaysianite weighing 464 grams is recorded to contain a "nest of vesicles" (Scrivenor, 1931), and a hollow Philippine tektite dredged from a depth of 50 feet burst on exposure. A hollow sphere 8 x 6 cms. in size from Malaya, burst while being sliced. One Philippine

tektite contained a smaller bubble 11 mm. across (Heide, 1938). A tektite weighing 10 grams from the Ouellé district, Ivory Coast, broke readily under the blow of a hammer, producing a small " explosion " and revealing an internal gas bubble 1 cm. across (Lacroix, 1934). The " explosive " effect produced in miniature the phenomenon described by Damour (1844, p. 4) in connexion with a large, hollow tektite sphere from Malaya (Plate XIV, fig. 3).

Some of the French Indo-China tektites have enormous gas cavities, others contain innumerable microscopic gas pores (Plates XVI and XVII), but are never pumiceous (Lacroix, 1932). Gas is abundant in tektites from Tan-hai Island and also (Plate XVI) from Kwang-Chow-wan (Lacroix, 1935b). Among the indochinites from Indo-China, large hollow forms are now largely represented by fragments which Lacroix stated often resembled the egg-shells of *Aepyornis*, but with walls of varying thickness. As in certain of the hollow australites, these fragments revealed that the internal cavity was not always centrally disposed in the original specimen. Where the glass of certain of the indochinites has been drawn out, the smaller gas pores have been elongated in the direction of elongation. Bubbles in pear-shaped indochinites are like those in " larmes bataviques ",* and many canals result at the openings of the elongated bubbles. No large gas cavities have so far been noted in the bediasites from Texas.

The presence of bubbles, and even " explosions " when bubbles are broken into, is no proof of the presence of considerable amounts of gas in tektites. At high temperatures, the weight of vapour or gas in a reasonably sized bubble will be quite small unless the pressure is high. The pressure at the time of formation of the bubbles was probably very low, perhaps only a few mm. Hg, or possibly negative pressure, so that the so-called " explosions " of broken tektites may in essence be " implosions ". Thus it is considered that bursting of the Malayan tektites on tapping or slicing was due to the fact that hot gas enclosed in hollow shells of tektite glass had contracted on cooling. A strong inward pressure was thus exerted on the glass shell after the enclosed gas had contracted (Scrivenor, 1931). When tapped or dropped or sliced, the hollow tektites then burst by inward collapse in the manner of an electric light globe when broken. The complete hollow tektites that escaped shattering on hitting the earth's surface on landing, evidently possessed more uniformly thicker shells than those now represented by fragments of hollow forms.

These conclusions are borne out by the findings of H. E. Suess (1951). Using so-called " gas-rich " tektites from the Philippine Islands, which are exceptionally rich in bubbles of various sizes, Suess showed that there was no measurable amount of gas present, and that the content of bubbles must represent a fairly good vacuum. The amount of gas obtained from $5\frac{1}{2}$ grams of this tektite was under 10^{-4} cc. SPT, the pressure in the bubbles being calculated as under 10^{-3} atmospheres (H. E. Suess, 1951, p. 76). It was considered that an estimate of the pressure of gas bubbles present in a Philippine Islands tektite, necessary to balance the surface tension of the molten tektite glass, would be 1 mm. to form the bubbles at zero external pressures, and it was thought that this would undoubtedly speak for an extraterrestrial origin of the tektites, although it does not prove it conclusively.

Some of the bubble cavities in moldavites have been regarded as due to the absorption of gases while these tektites fell through the atmosphere (F. E. Suess, 1900), the gas becoming expelled at a later stage during cooling. It has also been suggested that large bubbles indicated remelting of tektites under the

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* See page 195.

influence of an annealing heat, in a medium that allowed of gas escape (Selga, 1929, p. 25). These large bubbles have also been regarded as relics of gaseous products arising from reactions occurring when a (hypothetical) light-metal meteorite oxidized and volatilized in the terrestrial atmosphere (Lacroix, 1932). Lacroix was evidently influenced here by his observations concerning the abundant gas bubbles that were forced away from portion of a heated holo-sideritic meteorite from Tamentit oasis, Algerian Sahara, when touched with the tip of an oxy-acetylene flame.

The vesicular, sometimes scoriaceous surfaces (posterior largely) of most australite cores (Plate XV, fig. 3A) indicate the previous escape of small occluded gas bubbles from fluidal glass, and the fact that these posterior surfaces are evidently remnants of primary surface, while posterior surfaces of well-preserved flanges which are secondary structures, are not likewise bubble-pitted, points to this escape having occurred prior to the entry of australites into the earth's atmosphere. The pitted character of Philippine Islands tektites (Hodge Smith, 1932, p. 581), is also caused by escaping gases during cooling, and this likewise occurred in a pre-atmospheric phase of their history.

This no doubt applies in fact to all varieties of tektites with bubble-pitted surfaces, although Lacroix (1935b) regarded those on indochinites as secondary, classing them as "corrosions due to deformations of chemical origin" (Plate XVI).

It is most likely that tektites without these bubble pits have been much abraded and have thus lost their original surfaces. Such forms, if subjected to a later natural etching, develop a very fine pitting that is distinctive from true bubble-pitting.

Thin sections of australites reveal two different types of gas enclosures, developed in different ways. Primary bubbles with pronounced dark borders are spherical or sometimes elongated along flow directions. They developed in australites before the flanges were formed. Some are closely associated with partially resorbed lechatelierite pseudomorphs (fig. 22, E), and were released during original fusion of the parent material. Other primary bubbles resulted from boiling of parts of the tektite glass in the early phases of formation. A second type of bubble, without marked dark borders, occurs only around the equatorial periphery of flanged australites, near lines of union (Plate XII, fig. A). They are secondary in origin and were originally exposed as bubble pits on posterior surfaces near the equatorial edge, but have been partially, sometimes completely re-enclosed by flange-forming, plastic glass that flowed on to cool, bubble-pitted glass around the peripheries of posterior surfaces of the central body portions. Few of these re-enclosed cavities retain their identity as bubble-like structures; most became infilled with australite glass of slightly different composition and refractive index to that composing the walls of original pits.

The enclosed spherical bubbles of gas about the size of a pin's head in indochinites (Plate XVII), also elongated bubbles, are evidently essentially of primary origin.

From the physical viewpoint, the significance of gas bubbles in tektites, considered in conjunction with the flow-lined nature of portions of the glass in many tektites, lies in the fact that these phenomena usually indicate, in artificial

glass manufacture for example, rapid original formation of the glass, so that homogeneity could not be attained throughout. At the same time, therefore, all the gas bubbles could not be discharged from the viscous glass (Hammond, 1950).

Extraction, Nature and Significance of Included Gas.

The gas in Colombian glass was extracted and examined by Professor Henrich (see Döring and Stutzer, 1928). Ten grams of powdered glass were placed in a kathode vacuum, kept constant for several hours. The temperature was raised to 1,100°C. Gas was slowly evolved, and after three and a half hours, when no more gas was evolved, the released gas was pumped off with a mercury pump, measured and analysed. The 10 gram sample gave 8·30 cc. of gas measured at 0°C. and 760 mm. pressure. The volume percentage composition was determined and compared with other tektites and with gas from obsidian (Table 12).

TABLE 12.

Gas.	Colombian Glass (Henrich).	Moldavite Glass (Henrich).	Billitonite Glass (A. Brun).	Obsidian Glass (A. Brun).
	%	%	%	%
CO_2 ..	27·1	12·6	46·00	9·83
CO ..	24·4	33·1	47·13	15·21*
H_2 ..	35·3	41·1	6·66	—
CH_4 ..	2·2	tr.	—	—
O_2 ..	1·1	0·6	—	1·43
Cl ..	—	—	—	14·47
HCl ..	—	—	—	50·75
SO_2 ..	—	—	0·18	8·31
Total	90·1**	87·4	99·97	100·00

* = plus nitrogen. ** = a little nitrogen contained in remaining gas, but too small in amount to test for rare gases.

From these results (Table 12), it is deduced that terrestrial and cosmic glasses differ considerably in the nature and amounts of their gas contents. Terrestrial glass of the obsidian family contains mainly HCl and Cl_2, cosmic glasses are devoid of these gases, but contain appreciable amounts of CO, CO_2 and free hydrogen. That a high CO and CO_2 content is peculiar to tektites, was also remarked upon by Beck (1910). The conclusions are: (i) cosmic glasses formed in an atmosphere free of oxygen, and (ii) the Colombian glass spheres are cosmic on the basis of similar gas content to moldavites and billitonites.

The gas in the Paucartambo (?)tektite, determined by A. Brun (see Linck, 1926a), was extracted in a vacuum at 900°C. and calculated to contain 10 cc. at 0°C. and 760 mm. pressure. The gas, analysed by Professor Hüttig of Jena, consisted almost exclusively of carbonic acid gas. The gas content of the Paucartambo glass is a little greater than in other tektites (Linck, 1934). Although crystal-bearing, like the glass from Macusani, Peru, and thus different from other glasses accepted as normal tektites, Linck considered the gas content as indicative of a tektitic nature, because it is comparable in chemical composition with that found in other tektites. Accepting Linck's conclusion, Barnes (1940a, p. 492) considered that the Paucartambo tektite probably had a similar origin to accepted tektite glass, because of this similar gas content, even though the glass

was comparable in chemical composition to an igneous rock. Contemplating the possibility of tektite origin from the fusion of terrestrial sediments, Barnes commented that if gases in tektites do result from sediment fusion, then nitrogen should be more plentiful. Only very small quantities of nitrogen have been recorded in tektite gas analyses, and this may have been derived from the earth's atmosphere during the phase of atmospheric flight. If tektites do represent fused sedimentary material, then the shortage of nitrogen gas in them might well be explained in terms of origin from lunar sediments, from which little, if any, nitrogen would be derived.

Moldavites and billitonites have been shown to contain entirely different gas contents to terrestrial obsidian from Tji, Manoek River, near Garoet, Preangor district, Java (Beck, 1910). In each variety of tektite, CO and CO_2 predominated among the gases evolved on heating in vacuum at 900° C. Beck thought the gas in billitonites was so different from gas in terrestrial obsidian that F. E. Suess' reasons against the terrestrial origin of tektites, could only be strengthened by the results. On the other hand, Brun deduced a terrestrial origin for tektites on account of the presence of NH_4Cl, but Beck was convinced that the gas content indicated a cosmic origin.

Tektites from Tan-hai Island, analysed for gas by M. Lebeau, also have a predominance of CO and CO_2 and gave a yield per kilogram of 100 cc. of gas. Some nitrogen and hydrogen gas was also detected, but no HCl nor Cl_2 (Lacroix, 1932).

When Bohemian moldavites are heated to 1,000 C., or fused with Na_2CO_3, the rare gases He, Ne and Ar are obtained. It is believed that these gases were partly absorbed from the earth's atmosphere, the excess of helium per gram of material used in the tests being $1 \cdot 6 \times 10^{-5}$ (Paneth, Peterson and Chloupek, 1929). It is claimed that as glass is permeable to helium, this gas does not accumulate in tektites (Paneth, 1940).

The gas content of australites has recently been obtained and compared with that derived from a Philippine Islands tektite (H. E. Suess, 1951, p. 78). Nitrogen is lacking from both of these tektite varieties, while one australite reveals a considerable amount of CO compared to the other gases present (Table 13).

TABLE 13.

Tektite.	Total cc. g.	Analysis (per cent.).				
		CO_2.	CO.	H_2.	H_2O.	N_2
Philippine Islands tektite	0·11	21	56	6·0	15	—
Australite	0·14	6	92	1·5	tr.	—
Australite*	0·33	6	7	0·5	86	—

* = surface not mechanically purified. The amount of water seems to vary on the way the surface of the samples was purified, and seems to indicate that most of the water was picked up by the tektite at the earth's surface, and it is unlikely that the bubbles inside the specimens were created by water vapour.

Deviations of the isotopic ratio of oxygen (O^{18}/O^{16}) from the arbitrary standard in parts per mille for two tektites, obsidian and Darwin Glass, have been determined (Baertschi, 1951, pp. 112-113) as listed in Table 14.

TABLE 14.

Silicate.	Isotopic Composition.
Obsidian glass, Iceland	− 4·5
Java tektite	+ 1·0
Moldavite	+ 3·0
Darwin Glass	+ 7·0

These varying isotopic compositions are regarded as falling within the range of the terrestrial abundance.

Chapter VI.

THE CHEMISTRY OF TEKTITES.

Chemical and Spectrographic Analyses. Radioactive Content.

Many tektites have been analysed and the results appear in the works of Dufrenoy (1844-1847), von John (1889), Verbeek (1897), F. E. Suess (1900 *et seq.*) Clarke (1904), Hillebrand (1904), Summers (1909 and 1913), Mueller (1915), Mingaye (1916), Washington (1917), Lacroix (1932, 1934, and 1935), Novácek (1932), Dittler (1933), Koomans (1938), Heide (1939), Barnes (1940), and Baker (1956). Analyses selected from these works to show the composition range in each tektite group are compared with each other and with certain terrestrial rocks and glasses in Table 15. Refractive index and density values are included where available.

Table 15.

Chemical Analyses of Tektites, &c.

	Moldavites.			Bediasites.		South China Tektites.		
	1.	2.	3.	4.	5.	6.	7.	8.
	%	%	%	%	%	%	%	%
SiO_2 ..	77·69	80·73	82·68	73·52	77·76	74·60	70·58	74·56
Al_2O_3 ..	12·78	9·61	9·56	15·88	13·30	11·59	13·23	12·34
Fe_2O_3 ..	2·05	—	—	0·45	0·37		0·10	
FeO ..	1·45	1·93	1·13	4·64	3·36	4·88	5·08	4·66
MgO ..	1·15	1·59	1·52	1·38	1·19	1·87	1·92	1·82
CaO ..	1·26	2·13	2·06	0·06	0·04	2·76	3·92	2·40
Na_2O ..	0·78	0·37	0·63	1·30	1·41	1·11	1·43	0·92
K_2O ..	2·78	3·60	2·28	1·73	1·97	2·32	2·59	2·47
H_2O ..	—	0·02		0·08	0·02	0·13	0·20	0·07
TiO_2 ..	—	0·32		0·87	0·76	0·95	0·99	0·92
MnO ..	—	0·07	0·18	0·01	0·01	0·15	0·13	0·10
Total ..	99·94	100·37	100·04	99·92	100·18	100·36	100·17	100·26
R.I. ..	—	1·487	—	1·502	1·492		—	1·505
S.G. ..		2·343		2·397	2·357		2·445	2·419

Table 15—*continued.*

	Indochinites.			Malaysianite.	Philippine Tektites.		
	9.	10.	11.	12.	13.	14.	15.
	%	%	%	%	%	%	%
SiO_2	72·40	70·40	73·48	76·64	70·08	70·66	71·64
Al_2O_3 ..	12·68	13·65	12·50	11·36	13·61	12·08	12·53
Fe_2O_3 ..	0·23	0·17	—	0·06	0·15	1·78	—
FeO	3·59	5·13	5·28	4·39	4·81	4·52	5·32
MgO	2·34	1·94	2·26	1·29	2·16	3·65	2·79
CaO	2·75	3·00	2·06	1·48	3·48	2·97	3·42
Na_2O ..	1·68	1·57	1·05	1·56	1·99	1·62	1·21
K_2O	3·16	2·72	2·32	2·30	2·44	1·69	2·28
H_2O	0·43	0·16	0·05	0·22	0·08	0·15	0·19
TiO_2	0·74	1·03	1·01	0·99	0·79	0·63	0·98
MnO	0·06	0·15	0·10	0·10	0·15	0·16	0·10
Total ..	100·06	99·92	100·11	100·39	99·74	99·91	100·46
R.I.	—	1·512	—	1·497	—	—	—
S.G.	2·409	2·440	—	2·413	—	2·439	—

TABLE 15—*continued.*

	Java Tektites.			Borneo Tektites.		Australites.		
	16.	17.	18.	19.	20.	21.	22.	23.
	%	%	%	%	%	%	%	%
SiO_2 ..	73·73	70·62	71·14	69·32	70·90	68·91	73·59	79·51
Al_2O_3 ..	11·33	12·34	11·99	12·27	13·50	15·42	12·35	10·56
Fe_2O_3 ..	0·83	2·25	—	0·06	0·32	0·40	0·38	0·60
FeO ..	4·46	3·17	5·29	6·81	5·47	4·86	3·79	3·11
MgO ..	2·39	3·61	2·38	4·05	2·45	2·49	1·80	1·35
CaO ..	2·49	2·99	2·84	3·72	2·35	3·88	3·76	1·48
Na_2O ..	1·15	1·68	2·45	0·77	1·46	1·20	1·03	0·91
K_2O ..	2·32	1·57	2·76	2·18	2·17	2·50	1·93	1·25
H_2O ..	0·31	0·75	—	0·28	—	0·14	0·80	nil
TiO_2 ..	0·87	0·62	tr.	1·01	1·00	0·08	0·70	0·63
MnO ..	0·11	0·10	0·32	0·09	—	0·08	0·15	0·06
Total ..	100·18	99·70	99·17	100·53	99·62	99·96	100·29	99·65
R.I. ..	1·509	—	—	—	1·510	—	—	—
S.G. ..	2·436	2·442	—	—	2·457	—	2·428	2·370

TABLE 15—*continued.*

	Ivory Coast Tektites.			Peru (?)Tektite.	Colombian (?)Tektites.	
	24.	25.	26.	27.	28.	29.
	%	%	%	%	%	%
SiO_2 ..	68·00	68·60	76·56	70·56	76·37	75·87
Al_2O_3 ..	16·46	15·80	11·54	20·54	12·59	14·35
Fe_2O_3 ..	—	0·18	0·17	—	0·26	0·22
FeO ..	6·08	6·46	3·99	0·96*	0·48	—
MgO ..	3·38	2·88	3·60	0·11	0·17	0·29
CaO ..	2·00	1·40	1·62	0·78	0·79	0·00
Na_2O ..	1·45	2·35	1·32	3·80	3·36	3·96
K_2O ..	1·84	1·92	0·82	3·20	4·67	4·65
H_2O ..	0·27	—	0·29	—	0·97	0·33
TiO_2 ..	0·80	0·80	0·60	—	0·11	tr.
MnO ..	0·09	0·06	0·08	—	0·14	—
Total ..	100·37	100·45	100·59	99·95	99·91	99·67
R.I. ..	1·5178	1·5146	1·4991	1·486	—	—
S.G. ..	2·517	2·487	2·400	2·360	2·310	—

* = plus MnO

TABLE 15—*continued.*

	Schönite.	Sakado Glass.	Obsidian.	
	30.	31.	32.	33.
	%	%	%	%
SiO_2	46·69	75·11	75·52	64·00
Al_2O_3 ..	2·05	18·67	14·11	10·43
Fe_2O_3 ..	0·19	0·24	1·74	6·30
FeO	0·34	—	0·08	3·86
MgO	4·08	0·33	0·10	0·34
CaO	23·91	0·34	0·78	1·45
Na_2O	1·11	4·61	3·92	7·59
K_2O	17·71	0·64	3·63	4·59
H_2O	0·06	0·46	—	—
TiO_2	0·14	—	—	0·78
MnO	1·08	—	—	0·37
Total ..	97·36	100·40	99·88	99·71
R.I.	—	1·49	—	—
S.G.	—	2·362	—	—

Key to Table 15.

1. Moldavite, Budweis, Bohemia.
2. Moldavite, Lhenice, Bohemia.
3. Moldavite, Budweis, Bohemia.
4. Bediasite, Grimes County, Texas, U.S.A.
5. Bediasite, Grimes County, Texas, U.S.A.
6. Indochinite, Hai-nan Island, south coast of China.
7. Indochinite, Kwang-Chow-wan, South China.
8. Indochinite, Kwang-Chow-wan, South China.
9. Indochinite, Siam.
10. Indochinite, French Indo-China.
11. Indochinite, French Indo-China.
12. Indochinite, French Indo-China.
13. Malaysianite, Malay Peninsula.
14. Rizalite, Rizal Province, Philippine Islands.
15. Rizalite, Rosario, Philippine Islands.
16. Billitonite, Solo, Central Java.
17. Billitonite, Java.
18. Billitonite, Dendang, Island of Billiton.
19. Tektite, Borneo.
20. Tektite, Borneo.
21. Australite, Uralla, N.S.W., Australia.
22. Australite, Pieman River, Tasmania.
23. Australite, Curdie's Inlet, South-West Victoria, Australia.
24. Tektite, Akakoumoekrou, Ivory Coast, West Africa.
25. Tektite, near Ouellé, Ivory Coast, West Afrca.
26. Tektite, Akakoumoekrou, Ivory Coast, West Africa.
27. (?)Tektite, Paucartambo, Peru.

Key to Table 15—continued.

28. (?)Tektite, Tetilla, Colombia.
29. (?)Tektite, Cali, Colombia.
30. Schönite (" pseudo-tektite "), Källna, Schönen, Sweden.
31. " Pseudo-tektite " glass, Sakado, near Tokyo, Japan.
32. Obsidian, U.S.A.(*).
33. Obsidian, British East Africa(*).

Inferences on tektite origin, drawn from the results of chemical analyses, lack complete unanimity, and three different schools of thought have existed on this matter; one compared the analyses of tektites with those of terrestrial obsidian, another with those of terrestrial sediments, and the third maintains that tektite glasses are so unlike terrestrial materials as to warrant separation from them and inclusion in a group of extraterrestrial glasses.

Analyses of obsidian from near Seleska, Presõv-Tokaj mountains, Eastern Slovakia, were shown to be similar to those of moldavites in the SiO_2, Al_2O_3 and CaO contents, but the obsidian has a distinctly higher Na_2O and lower FeO and MgO content (Rosicky, 1934). It has also been suggested that the average difference between the chemical compositions of australites and obsidian was insignificant when compared with the differences between australites themselves (Dunn, 1912b, p. 10), and that the chemical analyses prove that tektites have a composition similar to acid volcanic rocks (Simpson, 1902; Dunn, 1914) like rhyolite-obsidian. It has also been stated that all tektites chemically approximate to glassy forms of terrestrial rhyolite, but that all the tektites are unusually richer in lime and magnesia (Merrill, 1911).

A second school of thought interprets the analyses of tektites as comparable with those of certain sediments (Linck, 1928, p. 228; Koomans, 1938, p. 78, and Barnes, 1940a, p. 543). The Paucartambo (?)tektite was regarded as chemically incomparable with obsidian since it approached terrestrial sediments in composition, but it was postulated that this tektite was derived from a celestial body on which clastic sediments occurred (Linck, 1928, p. 231 and 1934). The supposition of derivation from such a far-off source has been questioned on the grounds that such an hypothesis cannot be verified, and moreover, products of the same composition already exist upon the earth (Koomans, 1938). Then again, if all the analyses of sediments were adjusted for volatiles, at least one would be found to match any tektite analysis, whether the more acid moldavite or the more basic billitonite groups (Barnes, 1940a, p. 543). By studying the normative mineral composition of tektites and arranging them according to the C.I.P.W. classification of rocks, it has been found that the tektites could be classified into fifteen different groups, and among these groups, there occur four in which no igneous rock of similar classification is present (Barnes, 1940a, pp. 525-533). On the other hand, a comparison of the chemical criteria of detrital argillaceous rocks reveals a strong pointer to the fact that bediasites, and probably also moldavites and Ivory Coast tektites, appear to represent fused sediments. Indochinites, australites and billitonites on the same basis of comparison, appear to be more closely allied to igneous rocks.

Advocates of the lightning theory of tektite origin, have compared the chemical compositions of tektites with those of various fine-grained materials from which they consider tektites could have been formed on fusion by

(*) Nos. 32 and 33 J. P. Iddings—" Igneous rocks ", Vol. 2, pp. 114-146, John Wiley and Sons, New York, 1913.

lightning. Thus it has been postulated that the composition of tektites compares favourably with that of loess (Vogt, 1935), while australites have been compared in composition with the " red dust " whipped up from sub-arid to arid regions in Australia (Chapman, 1929).

Many other writers consider tektites are not comparable with such terrestrial acidic volcanic rocks as obsidians. It has been pointed out that soda and potash, for example, are lower in tektites than is normal for obsidian (Summers, 1913, p. 197), while the published analyses up to 1935 reveal a higher acidity coefficient and difference in the R_2O_3 : RO ratio (Loewinson-Lessing, 1935, p. 181). Moldavites have been shown to contain more oxides of iron and magnesium and less alkalies than any terrestrial rocks of the same acidity, and this supports arguments favouring a meteoritic origin of moldavites (Högbohm, 1900). Calculation of the possible mineral compositions of indochinites resulted in a considerable amount of the anorthite molecule, a fact regarded as incompatible with glasses or magmas of terrestrial origin having similar proportions of free-silica and orthoclase (Lacroix, 1930). The quotient from the sum of the iron and magnesia, divided by the sum of the alkalies, in addition to the ratios of lime, potash and soda, distinguish tektites from all terrestrial rocks, according to Mueller (1915). Comparisons of the normative mineral compositions of billitonites from Dendang, Island of Billiton, show that the theoretical values for tektites are naturally impossible for terrestrial magmas, because plagioclase with 43 per cent. An, besides 14 per cent. orthoclase, 36 per cent. quartz and 18 per cent. of meta-silicate of iron and magnesia, could not possibly occur in association with one another in terrestrial magmatic rocks (Dittler, 1933).

The composition of tektites is most closely related to silica-rich terrestrial granitic bodies, and thus compares with the composition of the outermost earth layer (Lacroix, Paneth, 1940, &c.). The peculiarity of the chemical composition of tektites lies in the conjunction of high silica with high lime, potash and alumina, and low magnesia, iron oxides and soda, and in these respects, they do resemble a few peculiar terrestrial granites (Washington, 1939). On the basis of speculative ideas of tektite origin from cosmic bodies such as the moon, Washington suggested the tektites were evidently derived from a body or bodies without an atmosphere, and any disproportions in composition such as those indicated above, have been regarded as not incongruous for a cosmic glass (F. E. Suess, 1909).

It would therefore appear that a chemical approach to the origin of tektites, has done little so far to provide a solution to the problem. It has shown that tektites have a few similarities and several differences when compared with known terrestrial rocks, whether igneous or sedimentary, and the possibility is by no means ruled out that extraterrestrial bodies exist, or existed, which were partly composed of materials similar to that comprising certain portions of the earth's surface, in particular more acidic portions.

Chemical Comparisons between the Different Tektite Groups.

When the chemical compositions of the different groups of tektites themselves are compared, it is seen (cf. Table 15) that there exist several, though not necessarily significant, differences, not only between the different groups, but between individual analyses in the same group. This is not entirely explained in terms of the analyses having been carried out by different analysts in different parts of the world and at different times. Some of the earlier analyses may be open to doubt, but nevertheless, it is in the very nature of

things that there should exist some minor variations from specimen to specimen and from group to group among the tektites. In view of the fact that the groups of tektites evidently arrived upon the earth's surface at different times in the latter part of the earth's history, the surprising fact is that all the different groups of the tektites do show such marked chemical similarities. This evidently points to an origin in a similar way from a similar portion of the cosmic laboratories.

A genetic relationship was shown by variation diagrams and by comparison utilizing the classification of Cross, Iddings, Pirsson and Washington*, between australites, billitonites and moldavites (Summers, 1913, plate VII). The Borneo tektites are chemically closely related to australites (Mueller, 1915) although corresponding with billitonites in physical characteristics, and the billitonites of Java are also closely allied chemically (Table 15, columns 16-18) to australites (Dittler, 1933). The javaites of Central Java (Table 15, column 16), however, have been suggested as being chemically intermediate between australites and billitonites (von Koenigswald, 1935), while one analysis by Dr. Wagner is comparable with analyses of indochinites and australites, but a little different from billitonites in possessing more SiO_2 (Heide, 1939).

Lacroix (1930) considered that all tektites possessed a remarkable constancy in chemical composition and showed (1929) that tektites from Northern Cambodia, French Indo-China resembled billitonites, while the Philippine tektites from Rosario are similar to tektites from Indo-China, Malaya, Bunguran Island and Billiton Island in all of their characteristics, including chemical composition (Lacroix, 1931). On the other hand, some analyses of rizalites from the Philippine Islands are more comparable to australites than to billitonites (Selga, 1930, p. 25). Analyses of australites from Western Australia, Central Australia, New South Wales and Victoria have been compared with one another and with analyses of tektites from Billiton and other islands of the East Indies, with the conclusion that they all show relatively close agreement.

The chemico-mineralogical characteristics of the Ivory Coast tektites are like those of other tektites from other regions, but with a few special peculiarities (Lacroix, 1934). The silica content is rather low in two of the three analyses made by M. Raoult, but is exceptionally high in the third analysis (Table 15, columns 24-26) compared to silica in indochinites (Table 15, columns 6-12). Alumina, iron and magnesia are all a little higher than usual, but magnesia is higher than lime and K_2O exceeds Na_2O in one analysis of the Ivory Coast tektites, but in the other two, soda is in excess.

Chemical Compositions of the Doubtful Tektites.

Analyses of the Colombian glass spheres (Table 15, columns 28 and 29) reveal excess of alumina over lime and alkalies, and paucity of lime compared to the andesites, dacites and plagioclase basalts of Colombia (Döring and Stutzer, 1928), and for this reason, added to others, have been sometimes regarded as tektites rather than as terrestrial volcanic rocks. The glass spheres are thus composed of vitreous alumino-silicate with impurities (Codazzi, 1925). Comparisons of the analyses of the Colombian glass with those of other tektites, show that soda and potash are much higher than normal for tektites, thus casting some doubt on the validity of a true-tektite-origin for the Colombian glass spheres.

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* Journ. Geol., vol. X, part 2, 1902.

The crystal-bearing (?)tektite from Paucartambo, Peru (Table 15, column 27) contains a somewhat greater alkali content than other tektites (Linck, 1934), while lime, as in Darwin Glass (Table 23) is below the average. However, the Paucartambo glass has an excess of silica and alumina compared to these components in obsidian, in this way agreeing with glass accepted as true tektite glass. Table 15 (column 27) reveals that the alumina content of the Paucartambo glass is even greater than in Colombian glass (Table 15, columns 28 and 29), and by far greater than any normal tektite. The ratio of potash to soda is less than one for Paucartambo glass, greater than one in the majority of tektites, but Linck thought this was no criterion because the preponderance of potash was not decisive, especially as such a preponderance was not shown by billitonites. Table 15, columns 16 to 20, however, show a preponderance of potash compared to soda in most of the analyses of the billitonites.

Chemical Composition of Two "Pseudo-tektites".

The two glasses, schönite and Sakado Glass, erstwhile suggested as being tektites, show very little chemical affinity with the true tektites. Soda exceeds potash in the analysis of one (Table 15, column 31) just as it does in terrestrial obsidian (Table 15, columns 32 and 33) and in slag formed from charcoal in the suction gas plant (Table 23, column XVII). In the other (Table 15, column 30), potash is far and away greater than soda, excessively so compared with tektites. The original glass from Schönen (=Skåne) in Sweden, which was described by Eichstädt (1908, p. 323) and named schönite by F. E. Suess (1914), was no longer available when queried by Zenzen (1940) and Wiman (1941), but they found that an analysis had been made by R. Mauzelius, about 1920, and this revealed a composition quite distinct from any tektite (see Table 15, column 30), and was actually comparable with bottle glass.

Variation Diagrams.

Various methods have been employed to portray diagrammatically the chemical compositions of tektites, and some of the latest used are reproduced herein to indicate the relationships between tektite groups and between the tektites generally and terrestrial rocks.

Among the earlier representations, Linck (1926a, p. 169) plotted the compositions of available analyses of tektites on an Osann triangle, wherein the three corners of the triangle represented CaO, Al_2O_3 and alkalies. The result of this plot indicated that tektites had little or no chemical resemblance to terrestrial volcanic rocks.

Based on the triangular diagrams of F. E. Suess (1914) and Dittler (1933), using the three oxides CaO, K_2O and Na_2O, more recent comparisons have been made between the tektites themselves and terrestrial rocks (Barnes, 1940a). In making these comparisons, it was found impossible to portray the compositions graphically unless certain groupings were made, or unless certain oxides were disregarded, because of the large number of oxides involved in the comparisons of such complex silicates as the tektites and igneous rocks. The triangular diagrams prepared by Suess and Dittler were therefore amplified by adding MgO to the comparisons, as indicated in figures 24 and 25.

The results of these comparisons show that the field for the igneous rocks is generally distinct from that for tektites. The igneous field overlaps the Ivory Coast tektite field in all comparisons, suggesting the possibility of an igneous origin for these tektites, or formation from a material little changed

from the composition of an igneous rock. Indochinites, australites, billitonites and Philippine tektites show similarities as evidenced from their overlapping fields in the comparative diagrams. Bediasites and moldavites do not show any

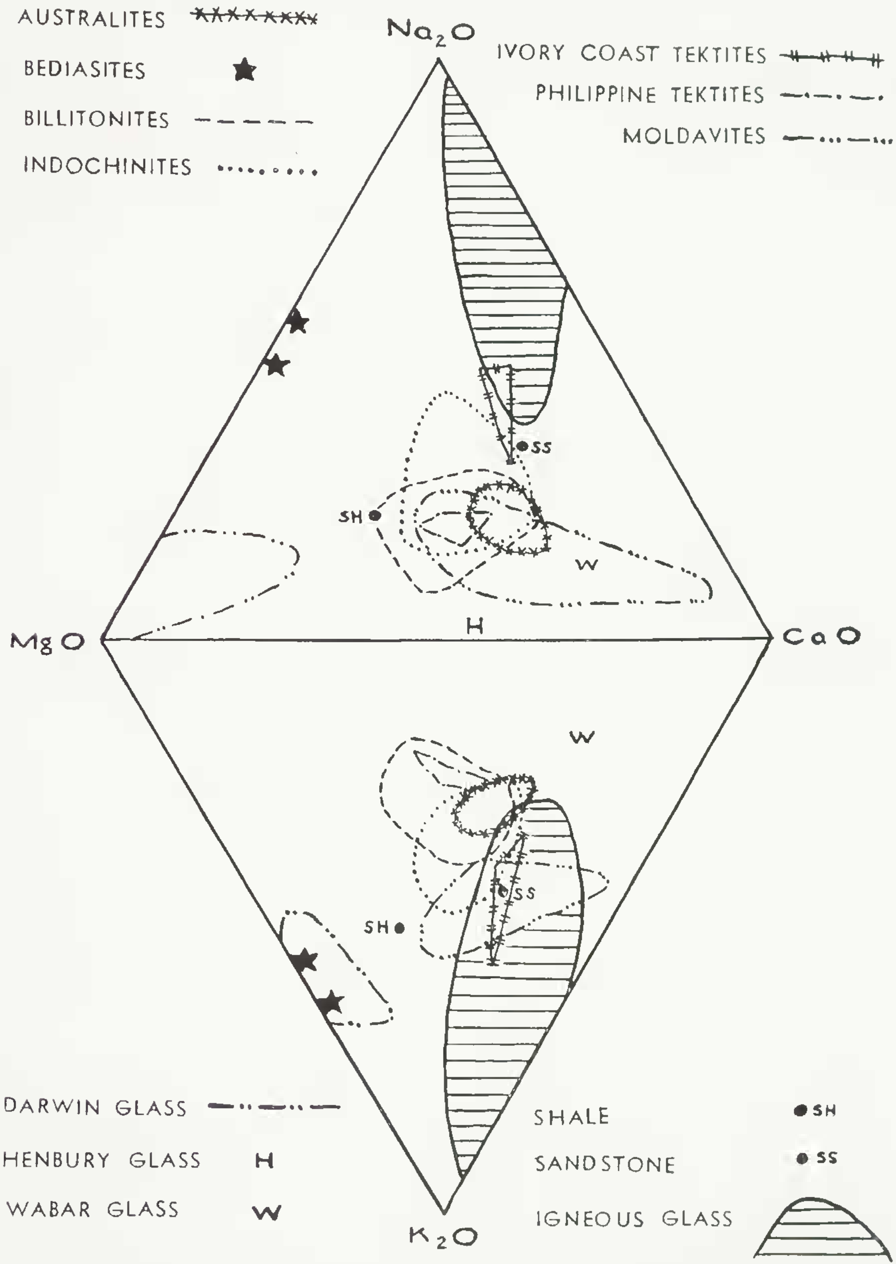

FIGURE 24.—Triangular diagrams using MgO-CaO-Na_2O and MgO-CaO-K_2O to compare tektite groups with igneous glass, two average sediments and meteorite crater glass (after Barnes, 1940a).

constant relationships to other tektites throughout the comparisons of the four oxides CaO, K_2O, Na_2O and MgO, and appear to reveal a similarity to certain sandy shales or argillaceous sandstones. If tektites represent re-fused materials from an extraterrestrial source, then the indication is that such extraterrestrial source possessed materials comparable with those known on the earth's surface.

From those materials, the chemical evidence seems to strongly point to bediasites and probably also moldavites and Ivory Coast tektites as representatives of sediments that became fused in an extraterrestrial environment, while indochinites, australites and bediasites were representatives of igneous types of acidic rocks that became fused in such an environment.

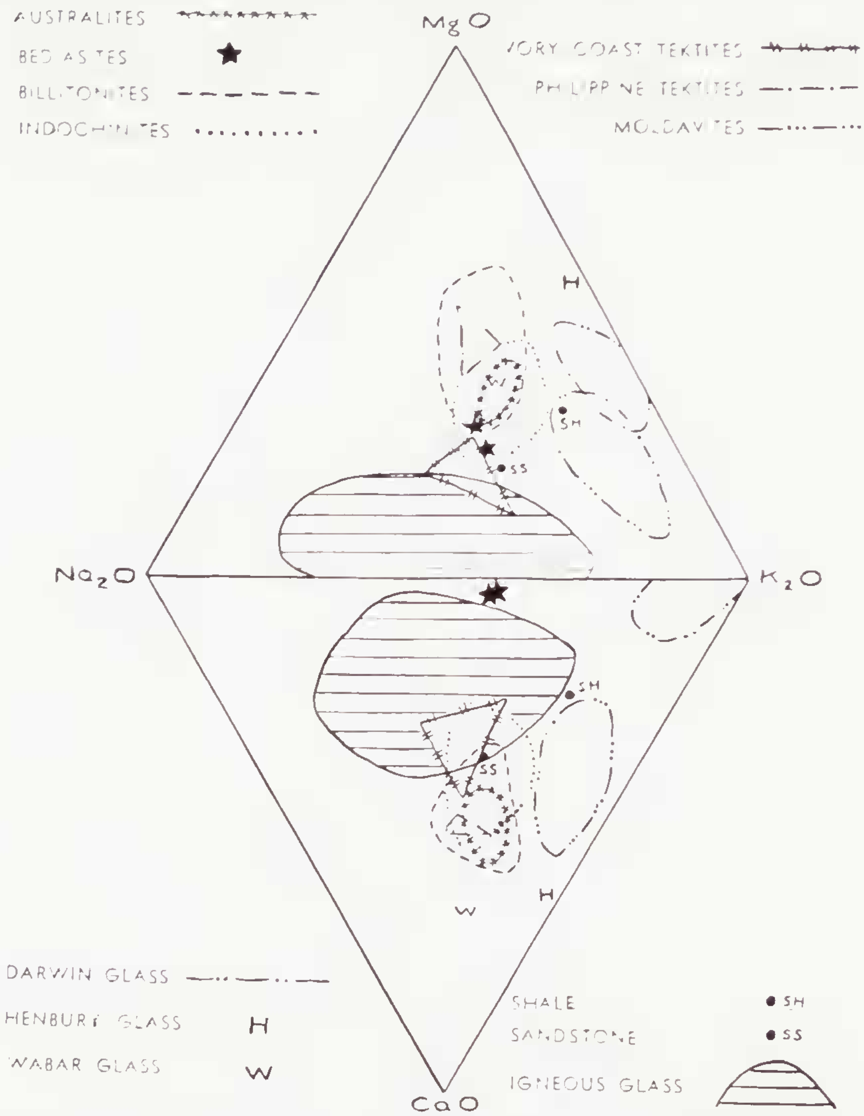

FIGURE 25.—Triangular diagrams using Na_2O-K_2O-MgO and Na_2O-K_2O-CaO to compare tektite groups with igneous glass, two average sediments and meteorite crater glass (after Barnes, 1940a).

In the following variation diagrams (figures 26 and 27) based on the work of Summers (1909, p. 425, and 1913, plate VII) and F. E. Suess (1914), the percentage of silica in tektites is represented along one co-ordinate, the percentages of other oxides along the other co-ordinate. Some workers prefer to compare the molecular numbers of the various oxides by means of variation diagrams, the molecular numbers being derived by dividing the actual percentages of the oxides found on analysis, by their molecular weights.

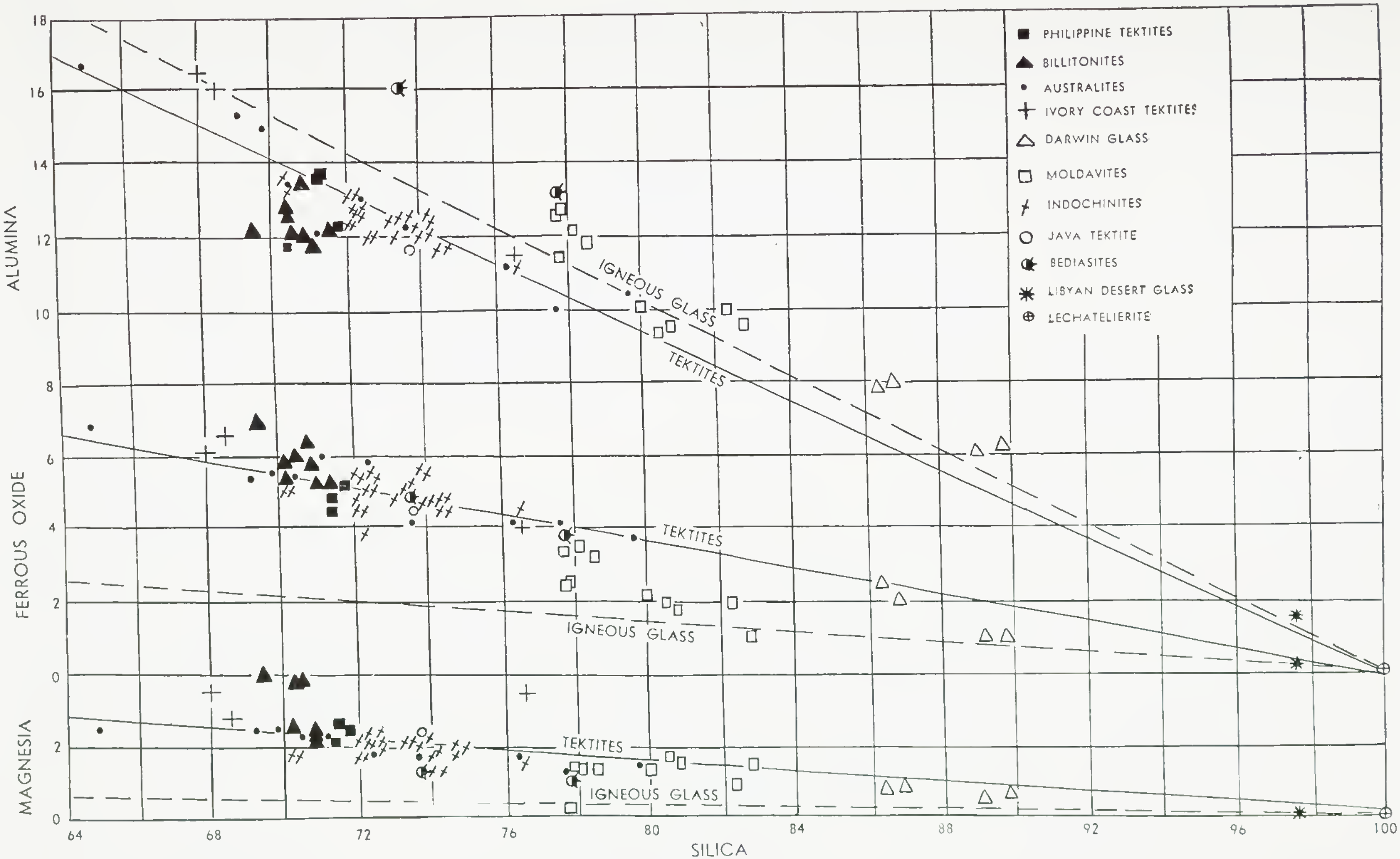

FIGURE 26.—Variation diagram for alumina, ferrous oxide and magnesia in tektites, silica glasses and igneous glass (after Barnes, 1940a).

Figures 26 and 27 show that Al_2O_3 is slightly higher in igneous glasses of terrestrial origin. FeO, MgO and CaO are markedly higher in tektites, while Na_2O and K_2O are significantly higher in igneous glasses.

It has been concluded that on the average, the content of silica and alumina in tektites is higher than in terrestrial igneous rocks and argillaceous sediments (Rankama and Sahama, 1950, p. 31). The presence of an excess of alumina as compared with lime and alkalies, is evident from Linck's (1924) average of analyses of twelve individual tektites. The calculated average as presented by Linck, shows: SiO_2—77·29 per cent.; Al_2O_3—11·07 per cent.; (Fe, Mn) O—3·21 per cent.; MgO—0·99 per cent.; CaO—2·21 per cent.; Na_2O—0·45 per cent.; and K_2O—2·48 per cent. (Total = 97·70 per cent.).

Spectro-chemical analyses of Tektites.

Analysis of a billitonite by spectrographic means, revealed under 0·005 per cent. GeO_2, 0·010 per cent. Ga_2O_3, 0·005 per cent. Sc_2O_3 and 0·001 per cent. Y_2O_3 (Goldschmidt, 1924).

The presence of C, Na, Ca, Ba, Sr, Li, Fe, Ni, Cr, Mn, Pb, Al, and Mg in a Bohemian moldavite was proved spectrographically by F. Exner, and a number of lines in the spectrograph that could not be definitely identified, were suggested as due to the rare earths.

Spectrographic analyses of indochinites and other tektites by M. Dureuil and M. Lebeau were made to ascertain whether barium and strontium were present (Lacroix, 1932). Neither these elements nor lithium, nor caesium were detected in Tan-hai Island tektites, billitonites, moldavites and Darwin Glass, but rubidium was constantly present. Rubidium has similar chemical properties and similar ionic radii to potassium ($Rb^+ = 1{\cdot}47A^o$; $K^+ = 1{\cdot}33A^o$), hence a close association is expected between the two. Using spectrochemical methods, the abundance of these two elements has been determined (Ahrens, Pinson and Kearns, 1952, p. 236) as in Table 16:

TABLE 16.

	Percentage K.	Percentage Rb.	Percentage K. / Percentage Rb.
Tektite, Annam, Indo-China	1·74	0·019	90
Tektite, Northern Cambodia, Indo-China ..	1·74	0·018	95
Tektite, Philippine Islands	1·83	0·018	100

Compared with a clay and a sandstone, spectrographic analyses of tektites and other natural glasses (Preuss, 1935) show the following Cr_2O_3 and NiO contents (Table 17):

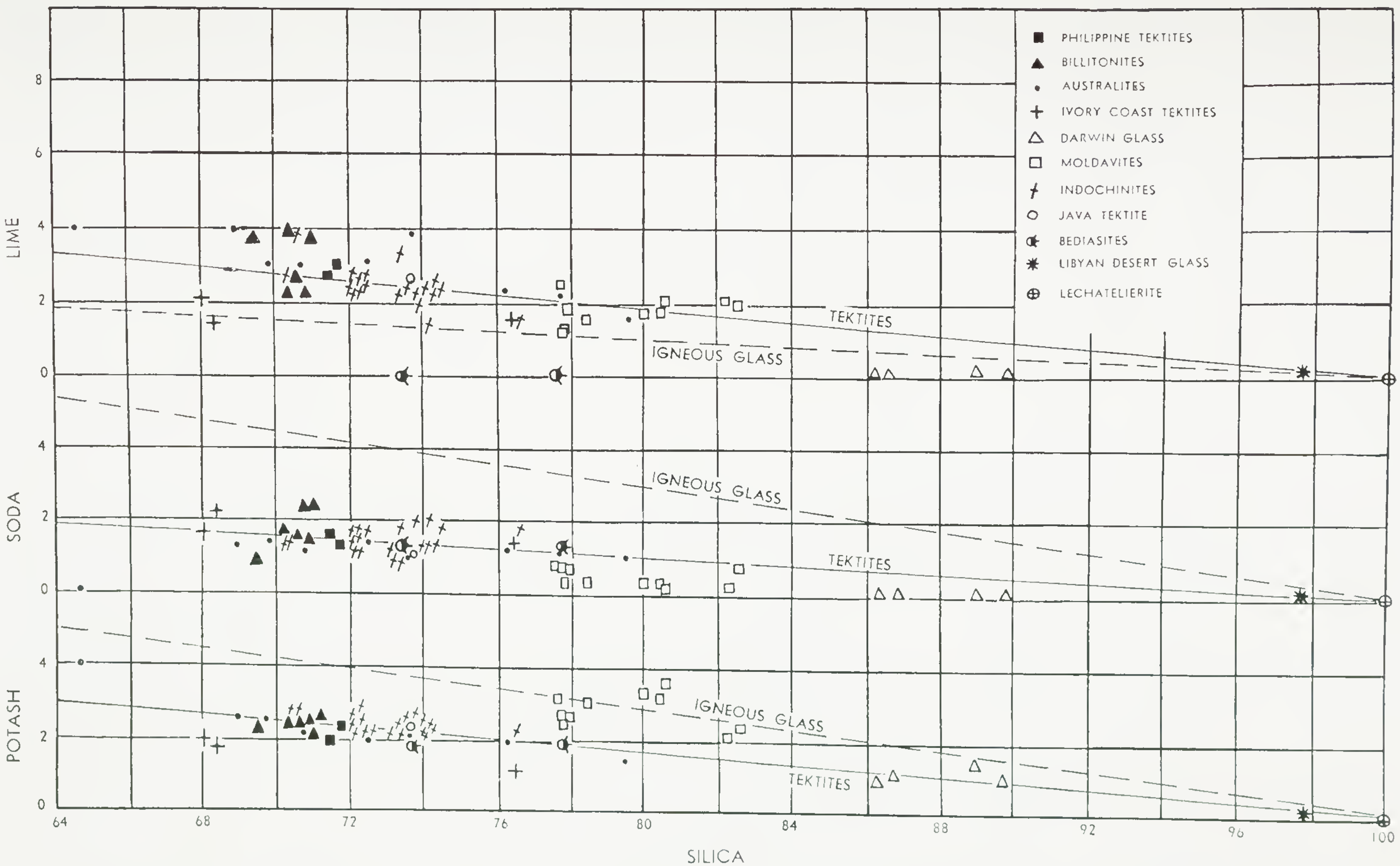

FIGURE 27.—Variation diagram for potash, soda and lime in tektites, silica glasses and igneous glass (after Barnes, 1940a).

TABLE 17.

	Cr_2O_3. (per cent.)	NiO. (per cent.)
Moldavites (mean)	0·006	0·002
Australites (mean)	0·013	0·0035
Tektites, North Indo-China (mean)	0·012	0·0035
Tektites, South Indo-China (mean)	0·030	0·025
Tektites, Billiton and Borneo	0·055	0·035
Darwin Glass, Tasmania	0·035	0·040
Silica Glass, Wabar, Arabia	0·008	0·150
Silica Glass, Henbury, Australia	0·007	0·120
Silica Glass, Libyan Desert	0·0006	$<$ 0·001
Sandstone, Henbury, Australia	0·008	0·004
Clay, Germany	0·022	0·006

Preuss thought that no definite conclusions as to origin could be deduced from these results, but the greater content of NiO in the glasses known to be produced from meteoritic impact (i.e. the silica glasses from Wabar and Henbury), does point to the improbability of the tektites and Darwin Glass having an origin as impactites.

Some of the minor elements detected by means of spectrographic analyses in tektites and in the lithosphere (Preuss, 1935, p. 412), are compared in Table 18, as the oxides.

TABLE 18.

	Tektites (per cent.).	Lithosphere (per cent.).
Li_2O	0·003	0·01
BeO	0·0005–0·001	0·0005–0·002
B_2O_3	0·004	0·001
SrO	0·02	0·05
BaO	0·05	0·05
TiO_2	0·7–1·0	0·8–1·0
ZrO_2	0·02	0·02–0·03
V_2O_3	0·01	0·015–0·02
Cr_2O_3	0·006–0·06	0·055
MnO	0·12	0·1–0·12
NiO	0·002–0·04	0·025
CuO	0·0003	0·01
Ga_2O_3	0·001–0·002	0·0015–0·002
GeO_2	0·0005	0·0005–0·001
SnO_2	0·0003	0·001
PbO	0·0001–0·0003	0·002

Table 18 shows that concentrations of Ti, V, Cr, Mn, Sr and Zr are the same in tektites and the lithosphere, so there is no distinction between the two for these elements. However, Ni, Cu, Ga, Ge, Sn and Pb show lower percentages in the tektites, of these, Cu, Ga, Ge and Pb always being less. It has been suggested that these elements could have vapourized away during the melting of the

tektite glasses (Heide, 1936), and so the results do not provide incontestible evidence supporting Spencer's Meteorite Splash Theory (Spencer, 1933a, p. 117) of tektite origin. In the ratio of Cr to Ni, tektites from Northern Indo-China (Cr_2O_3 = 0·012 per cent.; NiO = 0·0035 per cent.) resemble those from Australia; tektites from Southern Indo-China resemble those from Billiton Island (Cr_2O_3 = 0·03 per cent.; NiO = 0·025 per cent.). Since the amounts of the less common elements (Table 18) in tektites are of the same order of abundance as in the lithosphere, it has been concluded that some support is given to the theory of their terrestrial origin (Heide, 1936), but this deduction overlooks the possibility of similar materials occurring on an extraterrestrial body from which tektites were generated.

Spectrographic analyses of tektites from Solo in Central Java, show 0·026 per cent. NiO and 0·047 per cent. Cr_2O_3 (Heide, 1939). These are in the same amounts and ratio (Cr : Ni = 1·6) as for tektites from Southern Indo-China, Borneo and Billiton Island. Values of the nickel contents of other types of tektites, determined by Heide (1938) are: Bô Ploi, Siam = 0·006 per cent. NiO, Hai-nan, South China = 0·002 – 0·004 per cent. NiO, and Cambodia, French Indo-China = 0·021 – 0·028 per cent NiO. The various tektites of South-eastern Asia were grouped by Heide into a *central group* with Cr : Ni$<$2, including specimens from Java, Billiton Island, Borneo and South Indo-China, and a *peripheral group*, surrounding the central group in a large arc, with Cr : Ni = $>$2, and including tektites from Siam, Hai-nan Island, Tan-hai Island and the Philippine Islands.

The abundances of Sc, Sr, Ba and Zr determined for three tektites (Pinson, Ahrens and Franck, 1953, p. 253) are shown in Table 19:

TABLE 19.

	Sc (ppm).	Sr (ppm).	Ba (ppm).	Zr (ppm).
Tektite, Annam, Indo-China	< 1	85	300	200
Tektite, Cambodia, Indo-China	< 1	100	320	200
Tektite, Philippine Islands	< 1	100	420	200

It has been shown from the spectral transmission properties that some of the tektites from different parts of the earth's surface have similar absorption curves. In the australites, bediasites, rizalites and moldavites so tested (Stair, 1955, p. 49), the relatively high infra-red transmittances in the spectral region of 1000 to 2000 millimicrons, have been deduced to indicate that much of the iron may be in the unreduced state (Fe_2O_3) or in some equivalent combination as regards infra-red spectral absorption. Chemical analyses, on the other hand, record FeO in considerable excess over Fe_2O_3 in most tektites (see Table 15). If the chemical determinations of tektite compositions are correct, Stair (1955, p. 50) concludes that their spectral transmittances may offer a significant clue relative to the temperatures, pressures, type of atmosphere and other conditions existing on the meteoric planet at the time and place of tektite formation.

Radioactive Content of Tektites.

In an attempt to decide whether tektites were meteoritic or terrestrial, the radioactive contents (Table 20) of several tektites from three of the known groups have been determined (Dubey, 1933, p. 678).

TABLE 20.

	Ra x 10^{-12} per gm	Th x $10^{[illegible]}$ per gm.
1. Moldavite	1·07	1·08
2. Moldavite, Habri, Bohemia	1·02	1·60
3. Moldavite, Probsch	0·78	1·60
4. Moldavite, Radomilice, Bohemia	0·99	1·86
5. Billitonite	0·96	0·96
6. Australite, Lake Eyre District	0·96	0·50
7. Australite, Victoria	0·85	1·84
8. Darwin Glass, Tasmania	0·50	1·13
9. Glass (Old Beads)	0·48	—

In the tektites (Table 20, nos. 1 to 7), the radium content falls approximately between $0{\cdot}9 \times 10^{-12}$ and $1{\cdot}00 \times 10^{-12}$ grams per gram. A difference of $0{\cdot}1 \times 10^{-12}$ in different parts of the same sample, has no significance. The constancy of the radioactive content of tektites from widely separated parts of the world, clearly suggests some kind of genetic relationship. It is difficult to imagine that glass formed in three different continents from different raw materials should have the same radium contents, if formed as aerial fulgurites or by meteoritic splash. There is no probability of the tektites deriving their radium contents from iron meteorites in any way, because iron meteorites are poor in radium (10^{-14} per gram). The value of $1{\cdot}00 \times 10^{-12}$ per gram for tektites, seems fairly in accord with several determinations for granites, which represent the salic part of the earth's crust, and show a somewhat similar composition. The radioactive determinations strongly suggest that tektites were derived from some mass that agreed in chemical composition and radioactivity with the granitic layer of the earth.

Analyses of the Colombian Glass for radioactivity, gave a negative result (Döring and Stutzer, 1928).

Abundance of Elements in Tektites.

The abundance of elements detected chemically and spectrographically in tektites, have, insofar as is possible, been calculated (Buddhue, 1946, pp. 263-264) from a compilation of analyses made by Barnes (1940a, pp. 525-532) and ten other analyses. Darwin Glass, schönite, South American (?)tektites and Libyan Desert Glass are purposely omitted from consideration. The occurrences of rubidium and cobalt in tektites have been added to Buddhue's list (Table 21), since rubidium was detected spectrographically by Dureuil and Lebeau for Lacroix (1932) and by Ahrens, Pinson and Kearns (1952), while cobalt was detected spectrographically by Gaskin (Baker and Gaskin, 1946, p. 102). The values given as grams per gram by Buddhue, have been converted to percentages in Table 21. Numbers at the front of each element are atomic numbers.

TABLE 21.

1. Hydrogen	pr.	47. Silver	n.r.
2. Helium	pr.	48. Cadmium	n.r.
3. Lithium	pr.	49. Indium	n.r.
4. Beryllium	sp.	50. Tin	sp.
5. Boron	sp.	51. Antimony	n.r.
6. Carbon	pr.	52. Tellurium	n.r.
7. Nitrogen	pr.	53. Iodine	n.r.
8. Oxygen	49·3 per cent.	54. Xenon	n.r.
9. Fluorine	—	55. Caesium	n.r.
10. Neon	pr.	56. Barium	0·0018 per cent.
11. Sodium	1·01 per cent.	57. Lanthanum	n.r.
12. Magnesium	1·27 per cent.	58. Cerium	n.r.
13. Aluminium	6·72 per cent.	59. Praseodymium	n.r.
14. Silicon	33·96 per cent.	60. Neodymium	n.r.
15. Phosphorus	0·034 per cent.	61. Illinium	n.r.
16. Sulphur	pr.(?)	62. Samarium	n.r.
17. Chlorine	pr.	63. Europium	n.r.
18. Argon	pr.	64. Gadolinium	n.r.
19. Potassium	2·07 per cent.	65. Terbium	n.r.
20. Calcium	1·74 per cent.	66. Dysprosium	n.r.
21. Scandium	pr.	67. Holmium	n.r.
22. Titanium	0·71 per cent.	68. Erbium	n.r.
23. Vanadium	sp.	69. Thulium	n.r.
24. Chromium	0·0055 per cent.	70. Ytterbium	n.r.
25. Manganese	0·093 per cent.	71. Lutecium	n.r.
26. Iron	3·06 per cent.	72. Hafnium	n.r.
27. Cobalt	sp.	73. Tantalum	n.r.
28. Nickel	0·0031 per cent.	74. Tungsten	n.r.
29. Copper	pr.	75. Rhenium	n.r.
30. Zinc	n.r.	76. Osmium	n.r.
31. Gallium	pr.	77. Iridium	n.r.
32. Germanium	pr.	78. Platinum	n.r.
33. Arsenic	n.r.	79. Gold	n.r.
34. Selenium	sp.	80. Mercury	n.r.
35. Bromine	n.r.	81. Thallium	n.r.
36. Krypton	n.r.	82. Lead	sp.
37. Rubidium	sp.	83. Bismuth	n.r.
38. Strontium	sp.	84. Polonium	pr.
39. Yttrium	pr.	85. Alabamine	n.r.
40. Zirconium	pr.	86. Radon	pr.
41. Columbium	n.r.	87. Virginium	n.r.
42. Molybdenum	n.r.	88. Radium	$9 \cdot 5 \times 10^{-9}$ per cent.
43. Masurium	n.r.	89. Actinium	pr.
44. Ruthenium	n.r.	90. Thorium	0·0013 per cent.
45. Rhodium	n.r.	91. Protoactinium	pr.
46. Palladium	n.r.	92. Uranium	pr.

In Table 21, pr. = present; sp. = determined spectrographically, and n.r. = not recorded.

Where sufficient analytical data is known, a definite figure is given for the elements in tektites, but when there are not sufficient data, the element is only listed as " present ". A question mark indicates that the element in question has been reported chemically only once. Elements reported as having been detected spectrographically, have been discovered by means of a spectroscope, but not chemically.

Only five of the known elements have so far not been found in the group of extraterrestrial rocks comprised of iron and stony meteorites, troilite and tektites, and these elements are krypton, xenon, illinium, alabamine and virginium. Such elements are also particularly scarce on earth, and a similar rarity in meteorites may account for their apparent absence.

The helium in the tektites may be partially or entirely derived from the earth's atmosphere. The amount of neon reported from moldavites is $2 \cdot 0 \times 10^{-6}$ to $5 \cdot 0 \times 10^{-6}$ cc./g. (Paneth, Peterson and Chloupek, 1929). Elements 84, 86, and 88 to 92 are recorded as present by Buddhue (1946, p. 265) on the basis of the thorium and radium reported by Dubey (1933, p. 678).

Forty-four elements have so far been detected in tektites, and more may possibly be discovered with the further examination of additional specimens from various parts of the world. The significance of those known to be present, lies in the fact that they include the commoner elements comprising the sialic portions of the earth's crust, indicating that comparable materials occur in the extraterrestrial birthplace of tektites.

Although water is too low to list in the tables of chemical analyses, it has been reported by Friedman (1955) to occur in tektites in the range 0·002 to 0·008. These values are from one to two orders of magnitude lower than the values for terrestrial impactites, suggesting that the parent material for tektites contained considerably less water than any sialic igneous rock or argillaceous sediment on the earth.

It is probable that much significant and interesting data leading to a better understanding of certain problems relating to tektites, is to be obtained from a more extensive use of the spectrograph for trace element identification and evaluation, of the mass spectrometer for studying the isotopic abundance of elements retained as readily volatilized compounds, and of the spectrophotometer for obtaining special absorption characteristics over an extended range of wave lengths with the object of grouping and differentiating widely separated tektite showers, and determining their possible common origin in outer space (Hubbard, Krumrine and Stair, 1956, p. 778).

Chapter VII.

THEORIES OF FALLS. TIME OF ARRIVAL ON THE EARTH'S SURFACE. AGE OF TEKTITES.

Schools of thought have been divided as to whether tektites are still falling or whether there has been only one shower of tektites in each of the various zones of distribution. In some tektite strewnfields, the evidence points to only one shower. It cannot yet be proved that this holds for all known tektites.

There is no adequate evidence that tektites are still falling. The statement that " there is not a single reliable report of a piece of glass falling from the sky " (Paneth, 1940), summarizes the belief held by most workers with tektites, that the theory of continuing falls has yet to be proven beyond doubt. Supposed falls of glass observed by man, have been recorded from Europe and from Australia, but all have been discredited. In Europe, supposedly authentic falls were described by Brezina (1904, p. 41) and by Brandes (1905, p. 459). The first was recorded on the property of Igast near Walk, Livonia, where a fall of glass accompanied by detonation and a marked production of light, was reported to have been seen by reliable witnesses at 6 p.m. on 17th May, 1855. A chemical analysis of this glass was regarded as similar to that of moldavites from Radomilice, Czechoslovakia (Grewingk and Schmidt, 1864, p. 421), but Michel (1913) considered there was no relationship between the two, either chemically or in general appearance. The glass which was supposedly seen to fall, was described as dark brown to brown-red, pumiceous, varying from a finely vesicular and honeycomb-like fritted mass, to lava-like material with a smooth, slag-like skin (Grewingk and Schmidt, 1864)—a description that by no means seems to fit with the appearance of moldavites.

The second European fall, from Halle on the River Saale, Saxony, was reported (Brandes, 1905, p. 459) to have been noticed after 8 p.m. on 24th January, 1904, by the caretakers of a house. A violent, luminous phenomenon was observed close to a window of the house. The cause was found next day, when a charred heap of paper was seen to contain a slag-like stone the size of a fig and of brownish colour. Several people believed they heard a detonation and observed the phenomenon about the time of the reported fall. The " slag-like stone " was considered to be unlike a moldavite (Michel, 1913) because it contained many microliths not found in any true moldavites, and the chemical composition was very much different from that of moldavites and other tektites. F. E. Suess recognized the non-tektitic character of the Halle glass by its high lime content (8·75 per cent.) in the analysis made by von John (who thought the material was ordinary glass). The lack of alumina, the high lime content (lime content of moldavites = 2·24 per cent.) and the high content of alkalies (20 per cent.) all go to prove that the Halle glass is artificial. Moreover, it was excluded from the tektite group not only on chemical and physical grounds, but also because of the presence of charred paper in cracks in the specimen.

Another piece of glass was supposedly seen to fall at Halle Heide at 2.30 p.m. on 14th August, 1883. Some people heard a humming noise in the branches of a nearby tree, and noticed an accompanying appearance of light. In the steaming soil of a nearby spot, they reputedly found a slag-like, black stone that had loosened the soil to a depth of 10 cms. It was still too hot to touch and was lifted from the hole with two sticks. This glass was subsequently shown to be basic glass similar to the artificial glass spheres from Kuttenberg in Czechoslovakia (Michel, 1913). In thin section, it is light yellowish-green, and contains sharply defined crystals of leucite, pyroxene, plagioclase, apatite, olivine and melilite, and is not a tektite glass.

It is thus proven that the glasses supposed to have been seen to fall in Europe, do not add any confirmation to the theory that tektites are still falling.

In Australia, two records of the recent fall of australites (Simpson, 1935, p. 37 and 1939, p. 99) were strongly criticized by Fenner and also by La Paz (1944). The account was said to have been carefully prepared but not convincing. One of the supposedly recently fallen specimens was examined by Fenner (1935a, p. 139) and found to possess all the signs of having been on the earth's surface for a considerable time. One reaction to Fenner's criticism of this supposed recent australite fall at Lake Grace in Western Australia led to the remark that " with all the experience and record that Dr. Simpson has, it seems futile to dismiss his statement with a curt ' not convincing '," and it was called to mind that an American president had said " it was easier to believe that two Yankee professors would lie, than to believe that stones would fall from the sky ", yet even so, everyone to-day accepted the fall of meteorites from a cosmic source, " just as to-morrow they will accept the continuous fall of australites " (Hodge Smith, 1939, pp. 68-9). However, Fenner's extensive experience with australites undoubtedly places the matter beyond doubt, and is still further supported by Simpson's (1939, p. 99) record of a second observed fall having been corrected by Bowley (1945, p. 163). In connexion with this second so-called observed fall, a Mr. Hanson said he saw the australite fall in Kathleen-street, Cottesloe, but after careful enquiries, it was found that the specimen sent to Dr. Simpson for examination, came from 3 ft. 6 in. below ground level in a ballast pit between Narrogin and Merriden, where it was found by Mr. Hammer, who gave it to Mr. Hanson. Simpson did not therefore examine the object supposed to have been seen to fall, and the doubt surrounding it makes the evidence for a reputed recent fall of australites even more slender.

A feature of the search for fragments of the observed and photographed Kybunga daylight meteor, was the discovery of three large core-shaped australites in different localities within a radius of 15 miles or so of Kybunga, South Australia (Dodwell and Fenner, 1943, p. 14). It might appear at first that these australites were associated with the meteor in question, and thus provide an illustration of the recent fall of tektites. However, the australites found in this locality were observed to be flaked and abraded, and evidently belong to the general australite shower of pre-historic time.

A so-called fall of tektite glass, reputed to have occurred at Sakado near Tokyo, Japan, in 1910, can be dismissed, inasmuch as the chemical composition and physical characteristics of this glass reveal that it is non-tektitic.

The supposed evidence of historically recent falls fails to prove that tektites are still falling, and hence recourse is made to the theory of a single fall for each particular group of the tektite family. There is evidence to prove, however, that all the tektite groups did not fall at one and the same time, as would be demanded by the original Great Circle Theory of tektite distribution (David, Summers and Ampt, 1927), and proof of this will appear from the survey of evidence below.

It is in the very nature of things difficult to be sure whether specimens of tektites belonging to the same group or occurring in the same area, arise from one single fall or not. The opinion has been expressed (Lacroix, 1935) that the 2,362 complete and fragmented specimens of indochinites weighing 67·5 kilograms and spread over an area of 100 square miles in the Muong Nong district, Lower Laos, French Indo-China, resulted from one large fall that shattered on striking the earth. Then again, all moldavites in Czechoslovakia are believed to have been derived from a single meteoritic mass (Hanus, 1928), and hence they would thus have resulted from a single fall. Australites are believed (Petterd, 1903, p. 6) to

have been derived from one shower which occurred along a north-western track from Tasmania, through Victoria to the northern part of Western Australia and thence to the western islands of the Malay Archipelago. Several arguments have been advanced favouring the unity of origin of australites in both time and space (Fenner, 1935a, p. 139) so that it would appear there must have been but one shower of them. The three main objections to the theory of continuing falls for australites are: (1) their distinct chemical composition, different from terrestrial rocks and other tektites, (2) their small series of form-types, so unlike other petrological objects, and (3) their definite restriction to Australia. Australites are therefore pictured as having fallen as one vast shower "in a period geologically recent but historically remote", and if they could be imagined as still being prepared in the cosmic laboratories or formed in the earth's atmosphere, they would have little chance of invariably falling in one small area of "this swaying, spinning, speeding earth".

In support of the continuing fall of australites, it has been stated that no valid reason could be adduced against the supposition that tektites are probably falling to-day, as they have fallen from time to time for very many years (Thorp, 1914). Reasons advanced as favouring the continuing fall theory are (1) that hollow forms in particular could not have lain on the surface since Tertiary times, and yet remain unbroken, and (2) that australites found on the surface could not have been deposited at the same time as those included in the Deep Leads (Tertiary). They therefore could not all be contemporaneous. The occurrence of tektites in Australia, Bohemia and the Dutch East Indies has been suggested as due to successive returns of the same meteorite shower (Grant 1909, p. 446), and if so, the same meteor may return at a future date, and thus yield the only possible proof of the meteoritic origin of tektites.

The fact that some specimens of australites are fresh in appearance, while others are worn and dull from wind and river erosion, has influenced many writers who have argued that such differences could only mean a different time of arrival upon the earth's surface. Experience in collecting over 1,500 australites in the more temperate regions of Australia, however, has convinced the author that the reasons for such variations in appearance can be satisfactorily explained in terms of the time of release of different members of this tektite group from the enclosing superficial, usually incoherent sediment. The worn examples were released earlier and subjected to longer periods of exposure to atmospheric agencies. The fresh specimens have been buried for longer periods and completely protected under a cover of wind- or water-borne material, and have evidently only been recently released. Such specimens invariably possess a brilliant lustre and frequently maintain perfect outlines.

In order to test the two theories, that of a single fall, and that of continuing falls, recourse has recently been made to investigations of a large number of specific gravity values of australites from various parts of Australia (Baker and Forster, 1943, p. 396), in the hope that some finality might be reached. Although it was impossible to give added weight to the correctness of either theory, several interesting facts emerged from the results of statistical investigations of the specific gravity values. It was found that since the specific gravity frequency polygons indicated normal distributions, there are no outstanding statistical grounds for discounting Petterd's (1903) and Fenner's (1935a) theory of a single shower of australites. Had there been departures from normality, reasons would have existed for suspecting more than one fraternity within each australite shape group from each locality in the Australian strewnfield. It would then have been apparent that different falls of different composition had occurred, because the specific gravity variations would

reflect chemical variations. The fact that the specific gravity values of australites indicate a chemical gradient across Australia lends substantial support to any theory advocating a single shower. This reasoning is also partly substantiated when we consider that if two or more showers had occurred at different times, groups with higher specific gravities might be expected on statistical reasoning to have occurred in Eastern Australia. Such higher specific gravity falls in numbers of statistical significance are not forthcoming from Eastern Australia. Combined with the chemical gradient, strong supporting evidence is therefore at hand for advocating a single shower of australites.

On the other hand, the statistical investigations do not irrevocably eliminate the theory of continuing falls. The fact that there is no statistical evidence of the development of significant bimodal polygons in any shape group from any locality does not preclude several possibilities. There may have been two or more showers of the same shape group in different localities, or two or more showers containing different shape groups in the same locality. Moreover, several showers containing all shape groups might have occurred at different times in separate localities. The absence of bimodal polygons with statistical significance, however, does show there were not two or more fraternities in any given shape group, for if more than one shower of each shape group had occurred, each fall would have, of necessity, to be of the same specific gravity within certain limits, and hence of the same chemical composition. It is doubtful if such a condition would arise. Concerning the question "are tektites still falling?", there is still no convincing answer, but the concensus of opinion and a certain amount of evidence, point to the theory of a single fall being more likely in each of the tektite groups, although the groups themselves undoubtedly fell at different periods of earth history.

Times of Arrival of Tektites on the Earth's Surface.

While unanimity of agreement has been lacking regarding the questions whether tektites are still falling from the skies, or whether they are still being formed on the earth's surface, disagreement also existed for a long time regarding the times of arrival upon the earth, assuming an extraterrestrial origin. The various opinions expressed upon these matters depend on differing beliefs relating to the mode of origin of tektites. The original Great Circle Theory, for example, requires all tektites to have arrived on the earth at the same time, especially as only one great circle was advocated at the time this theory was put forward. Even as recently as 1951, it was stated that there was a contemporaneous fall of tektites in Bohemia, Moravia, Malay States and Australia on the basis of a Great Circle theory of distribution (Gutenberg, 1951).

However, tektites have been recovered from strata of different ages, so that the major groups could not have fallen at the same time as one another. Great showers of tektites fell on certain parts of the earth at widely separated geological periods. Beyer (1940) listed four of the tektite-bearing epochs as follows:—

(1) Ivory Coast tektites—Mesozoic.

(2) Moldavites—Mid-Miocene.

(3) Indomalaysianites—Mid-Pliocene.

(4) Australites—Post-Pleistocene or Recent.

The placing of the Ivory Coast tektites as Mesozoic is open to some doubt, since Lacroix (1934b), who described these tektites, gave no indications of age. Moreover, natural glass formed as long ago as the Mesozoic, would by now have developed some signs of devitrification, a condition to which Lacroix made no reference.

Other tektites of known age are the javaites, classed as Middle Pleistocene, the Philippine Islands tektites assigned to the middle or early part of the Late Pleistocene, and the bediasites which occur in gravels of Pleistocene age but may have been derived from the Eocene Jackson Formation (Barnes, 1940a, p. 553).

The Javanese tektites from Japara are found under conditions suggesting derivation from the same horizon as stone implements and the lower jaw of *Pithecanthropus erectus* (Middle Pleistocene). Tektites at Solo, Central Java, occur in a conglomerate bank among extensive fluviatile sediments, associated with *Stegodon trigonocephalus* Martin, *Elephas* cf. *namadicus* Falc. (= *E. antiquus* of Europe), *Axis lydekkerie* Martin and *Duboisia kroesenii* Stremme, which is the typical Trinil fauna in Java, and of Middle Pleistocene age. The conglomerate containing the tektites is nearly at the base of the Trinil System, so the maximum geological age is the beginning of the Middle Pleistocene or older, but certainly not the oldest Pleistocene.

Because the surface sculpture of the billitonites was thought to have resulted from the effects of desert conditions prevailing in the Island of Billiton between the Upper Jurassic and the Eocene periods, their geological age was regarded as Upper Jurassic to Eocene (Hövig, 1923). This theory is not accepted, and it is more likely that the age is Quaternary or Pliocene, since the billitonites were recorded as coming from sediments of this age on Billiton and from Quaternary tuffs in Java and Quaternary auriferous and platiniferous deposits in south-east Borneo (Verbeek, 1897).

The geographical and geological distribution of moldavites, and the nature of their exterior markings have been used in allocating a late Tertiary or Quaternary age to them (F. E. Suess, 1898). Later work has shown that the moldavite-bearing deposits of Moravia are younger Tertiary (Janoschek, 1934). Moldavite-bearing gravels are 60 to 100 metres above the valley bottoms containing Quaternary clay and loess, and can be correlated with the " Oncophora Sands " of the Helvetian stage (Miocene). Moldavites are rarely found in these valley bottoms, where the Quaternary deposits were evidently derived from the Helvetian beds into which the moldavites had fallen. The moldavites are thus separated by a considerable time interval from the younger tektites of Indo-China and Australia, which are certainly not pre-Pliocene in geological age. These facts strengthen the idea that the fall of tektites was thus not a passing phenomenon.

The discovery of a tektite at Tûol Prah Théat, near Kompong Speu, Cambodia, French Indo-China, in close association with a Buddhist relic of the seventeenth century, shows that it fell before that date (Lacroix, 1935). Discoveries associated with evidence of the activities of primitive man further show that such tektites fell over 25,000 years ago. Indochinites from South Annam, East Cambodia and Cochin China have been found resting on all formations except Recent alluvium (Saurin, 1935). The time of the fall to earth of these tektites was not later than the 10 to 15 metre terrace of Quaternary age in southern Indo-China, the tektites, which bear no chemical relationship

to the sub-stratum, occur in Quaternary deposits. In Kwang-Chow-wan, indochinites fell to earth after the formation of ancient dunes and before the outpouring of Quaternary basalts (Lacroix, 1932).

A precise geological age for Australian tektites has not been conclusively established, but they are most likely late Quaternary. They have been recorded 16 feet below the surface associated with rock crystal, angular quartz pebbles and roots and trunks of *Banksia* in the clay-drift of an old river course, in the marshy depression formed by Retreat Creek at Ingleby in the Otway region of south-west Victoria (Krause, 1874, p. 104). Others are found at the surface and in recent soils. It was originally thought that australites were not all of the same age, because, under similar conditions, some were perfectly fresh with a black, lustrous exterior, while others were dulled and showed signs of decomposition (Walcott, 1898, p. 50). Moreover, it was thought at the same time that the presence of these tektites in post-Pliocene drifts and on the surface of the ground, as well as their slight variance in composition, tended to support this belief. The australites also come from post-Pliocene drift material at Spring Creek, Daylesford, Victoria (Ulrich, 1866, p. 65). Several writers have suggested that the australites had their source in the Tertiary basic volcanic rocks of Tasmania and southern Australia, but this idea can be eliminated on the grounds that there is such a vast difference in chemical compositions between australites and the Tertiary basaltic rocks. Moreover, there is no obsidian, which is the closest terrestrial glass to tektites, in this region (Petterd, 1903). In Tasmania, it is believed that australites fell in post-Pliocene times, and that no evidence has come to light that would require the assignment of a date as far back as early or middle Tertiary for Tasmanian occurrences of australites, none having been found in undoubted Tertiary deposits (Twelvetrees, 1906, p. 60). At Mt. William in the Grampians, Victoria, the australites occur in the wash-dirt of Recent age, but not in the 6 or 7 feet of drift and sand formed in the later Recent period (Dunn, 1912b).

For australites generally, a post-Pleistocene age has been suggested (Fenner, 1935a, p. 140), and the reason for certain specimens appearing fresher and newer than others, is regarded as due to some being preserved from atmospheric attack under a cover of superficial sands and clays. In the Port Campbell region of southern Victoria, australites occur exposed on borrow pits, on old roads (last used in 1933), and partially buried in superficial post-Miocene clays and Recent soil (Baker, 1937, p. 166). The superficial deposits form a thin veneer to Miocene limestones, and since no australites occur in these limestones, they are definitely post-Miocene. Moreover, they do not occur in nearby Pleistocene dune limestone in this district, and are thus post-Pleistocene. Their occurrence in surface soils indicates a still younger geological age for such specimens, which are found on approximately the same horizon as a former soil horizon, probably early Recent. The fact that some of these tektites have been found on man-made structures (e.g., old roads) might at first suggest the possibility of historically recent falls, but such specimens were evidently carted on to the roads with material obtained from borrow pits and spread on the road surface during road maintenance. No australites have been found in townships within the centres of greater concentration in the australite strewnfield. An australite discovered early in 1949 on a roadway in the heart of the city of Melbourne is a worn specimen that was undoubtedly transported there in gravel used for road repairs.

At Lake Callabonna, South Australia, "gizzard-stones" of rock types common to the desert plains of the interior of Australia have been found associated with the skeletons of the giant extinct bird *Genyornis newtoni*

Stirling. These skeletons are of late Pleistocene to early Recent age, but no australites occur among these gizzard-stones, even though they occur well within the australite strewnfield. It is known that large living birds such as emus and plain turkeys utilize australites as gizzard-stones (Fenner, 1949, pp. 18–19). The inference therefore is that australites had not fallen to earth at the time *Genyornis newtoni* roamed the Australian interior, and hence they evidently appeared in the geological chronology of the earth in late Quaternary times.

The evidence so far put forward for the geological age of australites leads to the conclusion that they arrived upon the earth's surface in prehistoric times, probably middle or early Recent.

On the basis of a half-life of one million years for the radioactive isotope Al^{26}, it has been calculated from an Al^{26} specific activity of $0 \cdot 048 \pm 0 \cdot 013$ disintegrations per minute per gram for australites, and no Al^{26} activity for either bediasites or moldavites, that the approximate terrestrial age (i.e., date of fall) of australites is less than 500,000 years, while that of bediasites and moldavites is greater than 4,000,000 years (Ehmann, 1957). The Al^{26} originally present in bediasites and moldavites has thus decayed to much lower levels during their longer presence on earth surface. Geological evidence supports the relatively recent age of australites. Moldavites are much older and being Mid-Miocene (Janoschek, 1934; Beyer, 1940) hence fell to earth some 25 to 35 million years ago. Bediasites possibly fell to earth at an even earlier time, for although they are found associated with Pleistocene gravels, they were evidently derived (Barnes, 1940a, p. 553) from an Eocene formation, and on this basis, reached the earth's surface from space some 50,000,000 years ago.

Epoch when the Elements of Tektites were Formed.

Ratios of the isotopes of an element, one isotope of which is radioactive, will normally give the epoch when the elements were formed. Ratios of two elements, one of which decays with production of the other, give the time since there was opportunity for separation of parent and product, which is normally the time since solidification. The determination of the isotope ratio $^{39}K : {}^{40}K$ which serves as an age measure of the element in meteorites and tektites is readily determined owing to the radioactivity of ^{40}K. Preparations of KCl from tektites obtained from Indo-China, Moravia, Australia and the Philippine Islands all showed the same activity as terrestrial KCl (H. Suess, 1938). The conclusion therefore is that the elements of tektites were formed at the same epoch as those of the earth, and that tektites must have originated within the solar system, or else the matter of the whole galaxy is co-eval.

Date of Formation of Tektites.

Attempts to establish the date of formation of tektites by radioactive methods of investigation, led to the conclusion that their helium excess gave no indication of geological age (Paneth, Peterson and Chloupek, 1929). In an attempt to find a clue to the origin of tektites, mass spectrometric isotopic-dilution techniques have been employed to determine the argon content. Previous investigations showed that the bubbles present in some specimens of tektites, have a gas pressure of less than 10^{-3} atmcspheres, and that the total argon content is below the limits of detection by ordinary techniques of gas analysis. From the aspect of age determination by the argon method, diffusion is negligible. Samples of tektite glass of 10 grams weight were broken into fragments approximately 3 mm. across. With a known quantity of $97 \cdot 5$ per cent. Argon-38, prepared by neutron irradiation of NaCl, these fragments were placed in a vacuum in a stainless steel system containing 30 grams outgassed NaOH

flux at 400°C. The gases obtained were purified through copper oxide, a liquid air trap and a calcium furnace. The remaining gases were absorbed on activated charcoal, transferred to a mass spectrometer, and their argon isotopic composition determined (H. E. Suess, Hayden and Inghram, 1951, p. 432). The upper limits to the age of tektites tested from the Philippine Islands and from Australia, assuming Argon-40 was radiogenic, have been determined from this work as 73×10^6 years for a Philippine tektite, and 32×10^6 for an australite. If any argon has been lost since the initial formation of the tektites, then these estimated age values will be low. However, the indication is that the date of formation of tektites was much later than that of the solar system, and later than that of the ordinary meteorites, the tektites being less than [illegible] younger. It becomes evident from this work of Suess, Hayden and Inghram, that if the date of formation of the australites is approximately correct, then all theories of their terrestrial origin must be incorrect. For example, if formed 32×10^6 years ago, then australites from the Port Campbell district of Victoria should, if they fell to the earth at that time, be found in the Miocene sediments. The fact remains that these tektites are found only in post-Pleistocene deposits, and it is thus obvious that their date of formation and their arrival time upon the earth's surface are separated by something over 31 million years.

On the other hand, it has been suggested from age determinations by the argon method, that since tektites give much lower results than meteoritic stones, then the tektites are not of cosmic origin (Gerling and Yashchenko, 1952, p. 901). Determinations by the argon method gave high K, with very little Ar, thus yielding results of the same order as previously determined for australites and philippinites, thus:—

	K per Cent.	K^{40} per Cent.	Ar cc./g.	Ar/K^{40}	Age, years.
I.	0·0171	$2 \cdot 0 \times 10^{-6}$	$8 \cdot 0 \times 10$[illegible]	$7 \cdot 2 \times 10^{-4}$	$1 \cdot 2 \times 10^7$
II.	0·0228	$2 \cdot 7 \times 10^{-6}$	$3 \cdot 8 \times 10^{-7}$	$2 \cdot 6 \times 10^{-4}$	$4 \cdot 6 \times 10^6$
III.	0·0314	$3 \cdot 8 \times 10^{-6}$	$4 \cdot 2 \times 10^{-7}$	$2 \cdot 1 \times 10^{-4}$	$3 \cdot 1 \times 10^6$

I. = rizalite; II. = indochinite; III. = moldavite.

As an outcome of work of this nature, there has now developed a trend of thought reverting to the terrestrial volcanic mode of tektite origin. This is undoubtedly a backward step, inasmuch as no terrestrial mode of origin will adequately explain australite distribution over 2,000,000 square miles of territory containing no volcanoes of the requisite composition to provide such acidic objects as the australites. Moreover, the deduction that since tektites are younger than meteoritic stones, then they are not of cosmic origin, surely needs further investigation. Is there a valid reason for supposing that tekites must have formed at much the same time as stony meteorites? Why cannot they have been produced by later eruptions from an extraterrestrial body?

Summarising the general evidence provided by the various views expressed concerning the problem whether tektites are still falling or not, and the problems of the date of formation and time of arrival on the earth, it becomes evident that the different groups of tektites from the several zones of occurrence, are separated in their time of arrival by considerable periods of time, and that there must thus have been more than one shower of tektites during the earth's geological history. As far as the evidence goes, the period of earth history covered by tektite showers, is limited to post-Mesozoic history. If older showers

did occur, then they are no longer recognizable, and could well have been lost by devitrification and dispersal as unrecognizable fragments. Although it has not yet been conclusively established whether the individuals of each group of tektites all fell at the same time or as a continuing process, the evidence at present available weighs favourably on the side of the theory of a single fall in each tektite area. The known tektites on the earth's surface, are thus believed to have fallen in different, widely separated areas at different, widely separated times, but their date of formation in an extraterrestrial birthplace was by no means coincident with their time of fall to the earth. No tektites have been observed to fall in historical times, and there is no known means of predicting the possibility of future falls.

Chapter VIII.

THE ORIGIN OF TEKTITES.

THEORIES OF ARTIFICIAL AND TERRESTRIAL MODES OF ORIGIN.

The origin of tektites is much debated. Many of the postulates have been strongly opposed, no single theory has escaped criticism, and no single theory seems to explain all the aspects of tektites. Some theories are quite fantastic and cannot explain known facts relating to tektites, others seem capable of solving many of the problems, but not all, connected with the place of origin and the method of formation. Several major problems of tektite origin still remain unsolved and Woodward's remark (1894, p. 34) about australites, even now summarizes the position after 65 years additional research—" where they came from no one knows ", and this applies also to all other varieties of tektites. Most investigators to-day, however, favour an extraterrestrial mode of origin as most capable of explaining several fundamental aspects of the tektite problem.

Aboriginal peoples of most lands where tektites are found were acquainted with those objects long before white man started theorizing on their nature and source. Since the natives of Indo-Malaysia called tektites " sun-stones ", " star-dung ", " moon-balls ", &c., it is aparent they believed the objects fell from the sky, but there is no known record of any actually having been seen by natives to fall to earth. In fact, it has been pointed out that although tektites from Ting-an on Hai-nan Island, Southern China, are known to the natives as " crottes du diable ", this does not indicate that tektites were seen to fall from the sky, as the same name is also applied to stone implements (Patte, 1934). It is possible that some of the native names for tektites in Indo-China, imply that remnants of an ancient tradition bear evidence of observed tektite falls, but it becomes very necessary to be wary of folk-lore, because in certain districts in France to-day, belemnites and marcasite nodules from the Chalk are even now regarded as lightning stones (Lacroix, 1932). In the Sudan and other regions, polished axes are attributed a similar mode of origin.

There are no records or native names indicating that the fall of australites was witnessed by aborigines, although it is known from their folk-lore that they used tektites long before white man reached Australia. These remarks are put forward to indicate that there is nothing among the history or folk-lore of ancient peoples that would provide any reliable clue as to the origin of tektites.

THEORIES OF ARTIFICIAL ORIGIN.

In the light of present knowledge about tektites, theories that they were produced artificially can be briefly dismissed. Interest in them centres largely in tracing out the history of the development of theories on tektites, and advocates of an artificial origin have added nothing constructive to the problem. The only part such theories have played in the tektite problem, has been that of stimulating strong criticism against them, and the resultant development of more reasonable theories of origin.

Moldavites were originally thought to be either slags from a furnace or gas-works or pseudo-volcanic due to the burning of earth (Lindaker, 1792, p. 272), and have also been compared with the tears on artificially prepared glass plants (Makowsky, 1881, pp. 21 and 26, and 1882, p. 43). Other early writers supported an artificial origin (Rzehak, 1897, p. 69) and at one time it was asserted that they were produced accidently or purposely by man, savage or civilized (Hillebrand, 1905). Despite evidence to the contrary, an artificial origin was

still believed in as late as 1917, in some quarters, for both moldavites and australites were likened to moulded forms or to accidental forms produced without any purpose (Berwerth, 1917). Important arguments against theories supporting an artificial origin for moldavites, were put forward quite early in the controversy, and supported by chemical evidence (Klaproth, 1816; Wenzliczke, 1880, p. 9; Habermann, 1881, pp. 21 and 26 and Bares, 1899). Other arguments were supported by the lack of clouded patches or foreign particles in the clear tektite glass, and the claim that the Moravian glass objects with their high alumina content and high temperature of fusion, could not have been produced artificially with simple apparatus (F. E. Suess, 1900). Much of the early debate on the artificial origin of moldavites was centred about the finding of glass spheres at Kuttenberg, Oberkaunitz, Krochty (near Trebisch), Budweis and Unter-Moldau in Central Europe. These were all found within the major areas of moldavite occurrence, with which the glasses were confused until ultimately proved to be non-tektitic (Michel, 1913).

Australites from auriferous alluvial deposits in New South Wales have been described as appearing as if " cast in a mould " (Rev. W. B. Clarke, 1855, p. 403), although this mode of origin was not claimed for them. It is also recorded (Walcott, 1898, p. 43) that some people believed that australites were originally plastic materials that had been pressed by a saucer-shaped mould in the ground. An artificial mode of origin is chemically impossible, and it is difficult to entertain the belief held by earlier writers, that the aborigines were metallurgists who had control of temperatures exceeding 1,300°C. (Summers, 1909, p. 433).

There is nothing in common between the analyses of australites and the various rocks named as sources for these tektites.

There has never been any reason for believing that billitonites had an artificial origin (Verbeek, 1897), although they were thought of at one time as representing slags of tin (de Groot, 1880, p. 495) despite the fact that the unlikelihood of such a mode of origin had already been expressed (Van Dijk, 1879).

The theory of an artificial origin has received little more than passing comment in recent literature on tektites, most authors being in agreement that the tektites had a natural mode of origin (cf. F. E. Suess, 1916; Linck, 1926; Novácek, 1932; Lacroix, 1932; Loewinson-Lessing, 1935; Oswald, 1936, &c.).

SUGGESTED ORIGIN FROM NATURAL FIRES.

The formation of silica glass from burning straw (Plate XIX, fig. D) has led to suggestions that tektites may have originated from the conflagration of plant material or the burning of coal seams. The silica content of ash from burnt straw has been noted to be as high as in certain tektites, while Ca, Fe, and Mg are present in similar concentrations (Prior, 1927), but the idea of tektite formation from plant conflagration must be discounted, as such a theory would be precluded by the fact that a glass so formed would be rich in potash and phosphoric acid and poor in alumina. Moreover, the development of tektite shapes by such a process, could not be expected.

Materials produced from natural substances by fusion during forest fires and during the burning of coal seams, burning petroleum seeps and burning gas seeps, are often highly porous and contain recognizable detrital grains (Barnes, 1940a, p. 549). Such are not the characteristics of tektites, which are mostly compact,

and it has been shown that bediasites, for instance, have nothing in common with fused products resulting during the burning of coal seams north of the bediasite strewnfield.*

SUGGESTED ORIGIN AS CONCRETIONS OR ENCLOSURES IN ROCKS.

It has been suggested that australites might have formed as concretions in limestone (Jensen, 1915), but the complex flow patterns, symmetry of shape, possession of flange structures and the chemical composition scarcely accord with such a hypothesis.

Towards the middle of the nineteenth century, it was thought that the discovery of a " beautiful obsidian sphere " in soil with gneissic rocks (a glacial deposit), proved that the Moravian glassy objects (moldavites presumably), came from mountains of gneiss in Scandinavian regions (Glocker, 1848, p. 458). Glass spheres are unknown in gneiss, and it is believed that Glocker's specimen was not a true moldavite, but probably came from nephrite (F. E. Suess, 1900). Other authors also thought that moldavites came from gneissic rocks, and the sites of derivation were said to be on the Upper Moldau River in Czechoslovakia (Hanamann, 1893, p. 365). Although Helmhacker (1873, p. 281) had previously advocated an artificial mode of origin for moldavites, he believed that he had found their original source—namely, enclosed in the serpentine at Krems. All petrographers would doubt such a conclusion, and Helmhacker's specimen was evidently dark-green hydro-silicate of the opal type (F. E. Suess, 1900). Neither Schrauf (1880, p. 345) nor von Camerländer (1887) found moldavites in serpentine at the locality referred to by Helmhacker.

Basing her arguments on the occurrence of tektites and " pseudo-tektites " in the same regions of the Philippine Islands, Koomans (1938), regarded tektites as terrestrial products, stating that since " pseudo-tektites " correspond in composition to terrestrial magmatic rocks and tektites to clay sediments (see also Linck and Preuss), then, if it is accepted that etching occurs in soils, the tektites can have a terrestrial mode of origin—by melting of the clays in some way or other. However, this theory fails to provide a source of heat for the melting or a means of producing the shapes of tektites as known.

G. Henriksen, an inspector of mines in Norway, who circulated correspondence about tektites, stated in one letter from Tromsö, Norway to the Billiton Tin Company, Dutch East Indies † that " the volcanic or meteoritic origin of billitonites cannot be seriously considered. The billitonites are found on bedrock like gold nuggets, and, like gold nuggets, they have grown in place."

THEORIES OF ORIGIN BY ABRASION.

From their shape, it was thought that australites represented waterworn objects and that the obsidian from which they were derived would ultimately be found in situ. An almost spherical australite collected by Victor Streich in the Great Victorian Desert, was believed to have come from perlite by decomposition (Stelzner, 1893).††

* " Pseudo-Igneous Rock and Baked Shale from the Burning of Lignite, Freestone County, Texas ", by J. T. Lonsdale and D. J. Crawford, University of Texas Bulletin 2801, 1928.

† Copy of letter of 15th December, 1922, in the Victorian Mines Department's files.

†† Six other australites sent by Streich to Stelzner, were pronounced as being un-connected with an amerikanite mode of origin like the spherical specimen previously received, and were regarded as volcanic bombs.

Some australites were regarded as rolled and waterworn pebbles of obsidian, others as obsidian abraded by wind-blown sand (Merrill, 1911, p. 481). Such hypotheses as these are contrary to the known facts, and are quite untenable. Rolling and abrasion would destroy, rather than produce, such features of australites as their flange structures, flow ridges, &c. Moreover, outcrops of obsidian are still unlocated within hundreds of miles of the australite strewnfield. The situation was summarised over 40 years ago by the statement that " before they (i.e. australites) are subjected to attrition by water, abrasion by wind-borne sand, or suffer by natural flaking, they possess a striking symmetry which differentiates them from ordinary mineral products; it is mechanical and does not result from crystallization " (Dunn, 1912b, p. 3).

The fact that australites were erstwhile referred to as " emu-stones," recalls the fantastic belief held in certain quarters that they were small pieces of rock rounded and shaped in the gizzards of emus.

DESICCATION THEORY OF ORIGIN.

There is no support for the theory that tektites developed from the drying-up of silicate gelmasses as propounded for the origin of billitonites (Wing Easton, 1921) and of australites (Van Lier, 1933). The original theory was criticized and rejected by authorities such as F. E. Suess (1922), Van der Veen (1923), Linck (1928) and Lacroix (1932), and despite its revival subsequently by Van Lier (1933), nobody to-day would give any credence to this theory.

In terms of the Desiccation Theory, tektites were regarded as " xeroliths " or dehydrated gels developed under certain climatic conditions from the action of humic acids on underlying rocks. They were supposed to have developed their shapes in stagnant pools, where they were accompanied by humicsol or tannin (" schutzcolloide "), by the coagulation of colloidal mineral matter to form a gel, and subsequent drying-up. (fig. 28).

Tektites are never observed forming in this way, gelpools are not known to exist to-day, and tektites have been shown to be composed of glass with entirely different properties to those of gels. Tektites have a very high viscosity that progressively diminishes with increase of temperature and have a considerable range of temperature of fusion, whereas a hydrogel of silica loses water at relatively low temperature, cracks and falls to a powder. Moreover, the gel does not soften before its fusion point is reached, but rapidly passes from the solid to the liquid state. The Tyndall effect shown by transparent or translucent hydrogels, is not shown by tektites, and whereas dehydrated gels give a powder spectrum indicating a crystalline structure, tektites give the amorphous spectrum characteristic of a glass.

It is thus obvious from the physico-chemical and other evidence, that the Gel Desiccation Hypothesis of tektite origin is entirely fantastic and without a single element of truth.

TERRESTRIAL VOLCANIC THEORIES OF ORIGIN.

Because certain terrestrial volcanic rocks and certain worn, broken or etched tektites bore a few general resemblances to one another, several of the earlier known groups of the tektites have been regarded as having been derived from volcanoes. Thus the moldavites from Budweis in Moravia were said to be " glassy lava " (Mayer, 1788). Billitonites were thought to be obsidian

(Wichmann, 1893) and were regarded as the youngest volcanic products yet recorded from the Island of Billiton (van Dijk, 1879). They cannot be terrestrial volcanic, however, because the nearest volcanoes are too far distant from the tektite sites (Verbeek, 1897).

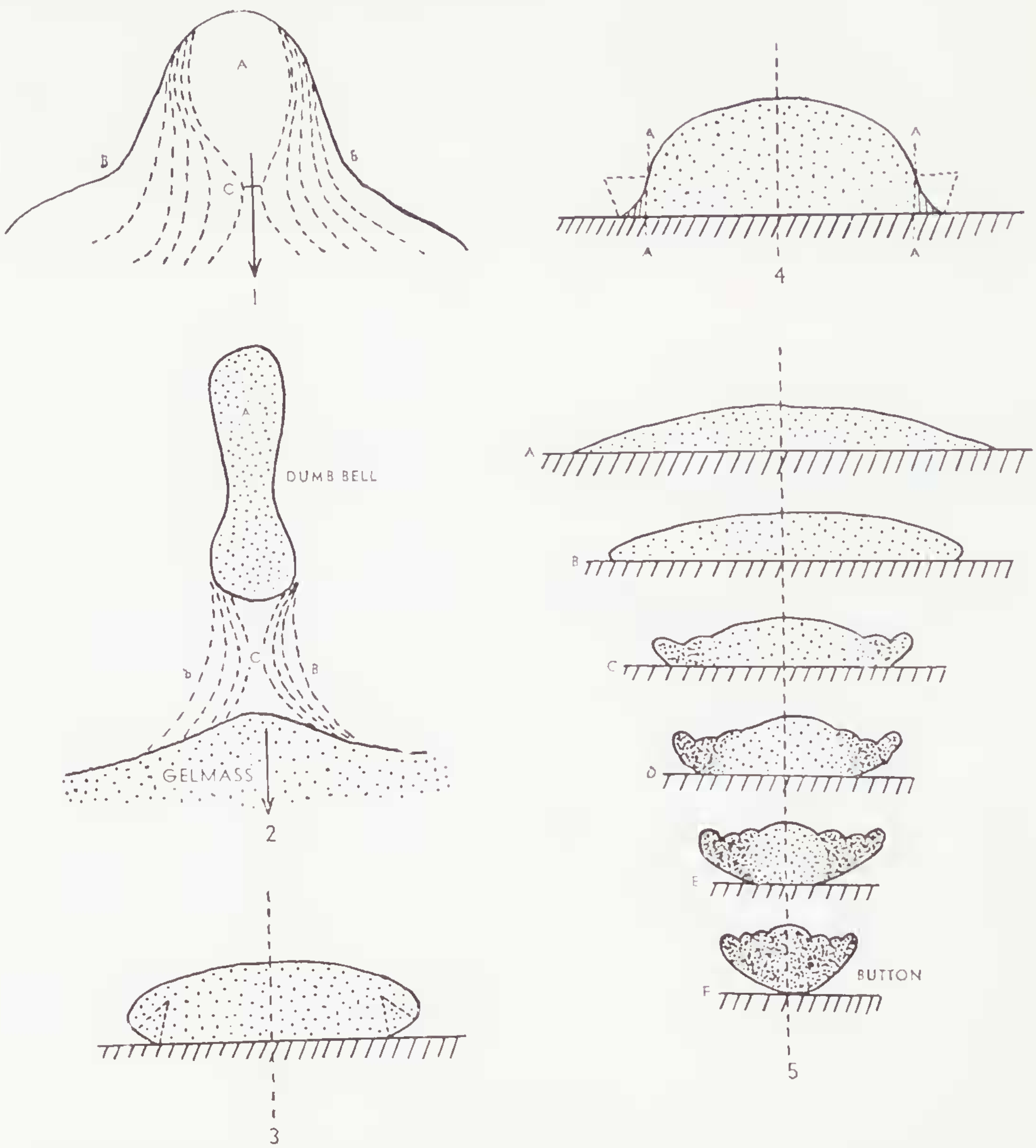

FIGURE 28.—Diagram illustrating the Gel Desiccation Hypothesis of australite development (after Van Lier, 1933).

Australites were accepted as terrestrial volcanic products, from the time of their initial discovery by white man and subsequently for over half a century. This is evident from their having been described as volcanic bombs (Darwin, 1844) and as "obsidian bombs," "obsidian buttons" and "obsidianites" up to the opening of the twentieth century (Clarke, 1855, p. 403; Ulrich, 1866, p. 65; Tate and Watt, 1896, pp. 70 to 71; Stephens, 1897; Twelvetrees and Petterd,

1897 and Blatchford, 1899, p. 36). The widespread nature of the Australian tektites was considered to indicate the existence of former volcanoes in many parts of the continent, and that these volcanoes had an acid to sub-acid composition. However, no such volcanoes have since been proved to have existed, and the widespread distribution of australites can be accounted for by other means.

Two other possible sources of australites regarded as volcanic bombs, have been suggested as (i) the north island of New Zealand, and (ii) the East Indies, more particularly Krakatoa, from which the objects were supposedly thrown out as lapilli and carried south by strong air currents (Simpson, 1902, p. 83). This theory is ruled out by the facts that no australites have ever been discovered anywhere in New Zealand, and they occur 1,000 to 3,000 miles distant from the East Indies where billitonites and javaites occur.

Shortly after the opening of the twentieth century, australites were still considered to be volcanic ejectamenta (Campbell, 1906, p. 22), although some authors were beginning to view the theory of a volcanic origin with suspicion (Spencer and Gillen, 1912). It was suggested that button-shaped australites might be spherulites from a lava with obscure flow structure (Dr. A. C. Lawson in Stephens, 1902), or that they resulted from the bursting of bubbles on the surface of some highly viscous lava about to solidify (Prof. Le Conté (in Stephens, 1902). It was also believed that Pelée's Tears were sufficiently similar to teardrop and dumb-bell-shaped australites as to demonstrate probable production from volcanoes under special conditions of favourable temperature, pressure or other physical circumstances (Moore, 1916, p. 55). It will be shown later, however, that australites are essentially secondarily modified forms of primary objects such as spheres, spheroids, ellipsoids, dumb-bells and apioids, whereas Pelée's Tears are fundamentally primary forms, and there is therefore no necessity to invoke a terrestrial volcanic origin on these grounds.

A stimulus was given to the volcanic theory of tektite origin with the elaboration of the "Bubble Hypothesis" (Dunn, 1908b and 1912). As early as 1893, hollow australites were thought to have formed by a swelling up process in unusually gassy portions of a terrestrial lava (Stelzner, 1893), and such glass bubbles were regarded as a convincing argument for the veracity of the "Bubble Hypothesis" (Thorp, 1913, 1914). The "Bubble Hypothesis" was founded on the basis of the existence of rare, hollow australites up to two inches in diameter (Plate XIV., nos. 1 and 2). These were supposed to have formed in periods of volcanic quiescence, when, by gentle ebullition, bubbles of glass were pictured as being carried up some five or six miles by hot ascending gases, and borne away from their volcanic source by air currents. Wide dispersal over Southern and Western Australia was explained by drifting for considerable distances under prevailing air currents. Subsequent examination of the flat, disc-shaped australites (cf. Plate V, fig. E) led to the conclusion that such forms did not favour the Bubble Hypothesis (Dunn, 1916), but the hypothesis was revived with the observation that a bubble of glass was formed by water dropping on hot slag, and the idea was extended to the possibility of glass bubbles developing when rain, hail or snow fell on to molten lava in a volcanic crater (Dunn, 1935). The only subsequent support given to Dunn's Bubble Hypothesis was based on the occurrence of elongated bubbles in indochinites and partly broken bubbles among rizalites and moldavites (Buddhue, 1940), but such observations provide no proof whatsoever of glass bubble formation in volcanic craters. Other authors are convinced

that such glass bubbles could be readily formed by other means, such as by any viscous liquid propelled through the air automatically enclosing volumes of air (F. E. Suess, 1909) or from the fusion of a glassy meteorite (Scrivenor, 1931). Recent studies of the curvature of australite surfaces (Baker, 1955a, 1956), indicate that all forms, including the glass bubbles, evidently had their birthplace in an extraterrestrial environment. No australites have ever been found with attached portions of the bubbles postulated as having drifted away from a volcanic crater, and no craters are known in the australite strewnfield in which the lava was ever as acidic as the composition of tektites. Moreover, no glass bubbles have yet been observed drifting away from volcanoes. Further objections to the Bubble Hypothesis are included in Chapter X, dealing with origin and nature of the shapes of australites.

Attempts to bolster volcanic theories of tektite origin came from the belief that certain acidic volcanic rocks and the tektites were similarly etched (Merrill, 1911 and Wright, 1915, p. 280). The possession of similar flow patterns by different materials, however, is by no means proof that tektite sculpture was formed in the same way as obsidian flow structure.

Objections to Terrestrial Volcanic Origin.

Hypotheses advocating a volcanic origin for tektites have been strongly criticized on various grounds, and few authors nowadays would favour such a mode of origin.

There are no igneous rocks from New Zealand, the East Indies, Australia or Tasmania with compositions comparable to australites (David, Summers and Ampt, 1927, p. 186), thus discounting volcanoes as a source for these tektites. Obsidian has been received from Samarai in New Guinea (Dunn, 1914), but no australites are known from anywhere in New Guinea, and terrestrial obsidian is not fundamentally related to tektites. The volcanic Bubble Hypothesis was completely exploded on physical grounds (Grant, 1909, p. 445) and on geological and chemical grounds (Summers, 1909, p. 435 and 1913, p. 193). There are no signs on australites of the supposititious fracture due to the breaking away of a bubble as is required by the Bubble Hypothesis, and the forms of australites are not those assumed by a liquid drop hanging from a bubble. Moreover, the formation of a dumb-bell-shaped australite by the postulated union of two separate bubbles is quite inadmissible. Then again, the pressure in a liquid bubble is determined by the total curvature of its inner surface and by the surface tension of the liquid. Since the upper and lower surfaces (i.e., posterior and anterior of modern terminology) of australites are both convex, the attachment of a bleb to a bubble in the manner conjectured by Dunn, is a physical impossibility because of the pressure inside the bubble; it would be impossible for one part of the interior to be convex (i.e., the top of the postulated bleb) and another part concave (i.e., the inside walls of the glass bubble). It has also been experimentally verified (Grant, 1909) that it is impossible to make a vacuous glass bubble strong enough to withstand air pressure and yet float in the atmosphere. A mass of liquid in motion, however, can assume the shapes of spheres, and with rotation, oblate spheroids, prolate spheroids, apioids and dumb-bells can be developed.

Other objections to australites having had a volcanic origin hinge on the widespread distribution and on the places where they have been found. Their occurrence on the Mallee Plains, for example, precludes a volcanic origin (Armitage, 1906, p. 100), and so does their occurrence in considerable numbers on the limestone Nullarbor Plain of South-Central Australia.

A volcanic origin for tektites also meets with other difficulties. They have shapes unlike any known in volcanic ejections, and differ from ejectamenta in their colour, compact character, rarity of bubbles and microliths, scarcity or lack of water in their composition and their very rare occurrence on or in volcanic soil (F. E. Suess, 1909).

THEORIES OF ORIGIN BY LIGHTNING.

A few writers have suggested that tektites were formed by electrical discharges, some believing that lightning had fused dust particles in the earth's atmosphere, others that lightning fused material where it struck the earth's surface. There are but few adherents to this theory to-day.

Moldavites have been compared with fulgurites from Mt. Blanc in Switzerland (Rutley, 1885) and the comparison thought to be not only admissible but positively instructive. No matter how applicable such a comparison may be, a similar comparison could not be made between australites and fulgurites (Walcott, 1898, p. 27), but nevertheless, australites have been regarded as *aerial fulgurites* and suggested as having been developed during cyclonic storms (Gregory, 1912, p. 36; Chapman, 1929 and 1933, p. 876). The basis of this theory is that electrical discharges fused dust in the atmosphere during storms, but no such " aerial fulgurite " has ever been picked up during a storm or after, and the opinion has been expressed that it seems hardly probable there would be sufficient dust in the atmosphere for electrical fusion to be realized, and there are no obvious arguments in favour of australite origin by fusion of dust during lightning discharge, (Summers, 1913, p. 195).

Approximate calculations show that there is probably enough dust in the path of a lightning stroke traversing a dust cloud 500 metres thick, to form one australite of 5 grams weight, but there is no known physical means of collecting all the dust in the path of the stroke, from top to bottom or side to side of such a dust cloud, fusing it and shaping it to form the well-known forms possessed by australites, at the same time causing some forms to rotate to develop the typical figures of revolution, and then modifying these to develop the secondary shapes. Moreover, this phenomena would have to occur some 10,000,000 to 20,000,000 times at least, in order to produce the estimated number of australites that have fallen to earth over Australia. Unfortunately for the lightning discharge hypothesis, there is not the variation in chemical composition among the australite members of the tektite family, that would be expected across the 2,000,000 square miles of the australite strewnfield, if formed by the fusion of dust derived from the various portions of this vast area. Much of this dust comes from basaltic areas, and is thus too basic in composition to form australites on fusion. The examination of " red rain " and the dust from " red snow " collected in parts of Victoria, reveals olivine and zircon among the constituents. The chemical compositions of australites (Table 15, columns 21 to 23) reveal no large amount of FeO and MgO, and even less zirconia (cf. Table 18).

It was believed in some quarters that the bubble types of tektites were formed by lightning discharges through dust clouds (Vogt, 1935), and were thus " aerial fulgurites," but there is no evidence in support of this idea, which at the outset does not explain why the included gas in bubbles formed in this way should be CO_2 and CO essentially, with no trace of the nitrous oxide that frequently attends lightning discharges.

Several suggestions have been advanced in attempts to show that tektites might be the same in origin as the types of fulgurites developed where lightning strikes the earth's surface. It has been stated quite dogmatically that the discharge of an electric spark into sand or loose soil, sometimes formed blebs of well-fused glass, usually shaped like buttons or dumb-bells, and from their prevalence in the desert regions of Australia, are called australites (Park, 1914, pp. 130 to 131). It becomes obvious that the author of this statement was unacquainted with the nature and mode of occurrence of australites, for they are totally unrelated to lightning discharges and are by no means limited to "the desert regions of Australia," and all the evidence completely militates against such a mode of origin.

The features of fulguritic glass have been clearly described by Anderson (1925) and others, and from these descriptions and from inspection of many fulgurites (see Chapter XVI), it becomes self-evident that fulgurites are in no way comparable with or related to australites in their mode of origin.

Nevertheless, the idea of tektite formation from the fusion of sediments on the earth's surface by lightning has recently been revived in an attempt to create enough interest to cause further investigation of terrestrial possibilities, before accepting meteoritic hypotheses with their "unproven and unprovable postulates" (Barnes, 1940a, p. 555). It was admitted that the definite shapes of australites and some indochinites were a stumbling block to the lightning theory of tektite origin, but the author of the revival of this idea was influenced by the discovery of accidentally formed shapes similar to some tektites, resulting from a broken power line arcing through sandy soil in Freestone County, Texas. Some molten drops from this process were propelled into the air, and assumed shapes resembling pear-, tear-, sphere- and deformed-shapes of indochinites like those figured by Lacroix (1932). Glassy, nearly spherical beads, one-sixteenth to one-quarter of an inch in diameter, formed by a lightning flash fusing concrete on a sidewalk in Detroit, Michigan, United States of America, have also been thought to bear some resemblance to tektites (Hill, 1947, p. 923). Several of the small number of scattered beads of glass were encrusted with particles of unfused concrete. Tektites never show attached parent rock fragments, and moreover the shapes of the glass beads would not be the same as those possessed by australites, where the final forms as found on the earth's surface, are those of modified primary shapes (see Chapter X).

The mode of formation of tektites as suggested by advocates of the lightning theory of origin, breaks down for similar reasons as some of the items advanced herein against the "aerial fulgurite" theory. Apart from the difficulty of explaining the remarkable shapes of australites, the lightning theory of origin breaks down when it is considered how very variable are the substances exposed across the vast australite strewnfield. The composition of these substances (soils, sands, clays and the like) from place to place in the strewnfield, is far more variable than is the composition of the australites. This becomes even more accentuated when tektites from all the other strewnfields on the earth's surface are considered in regard to the substances on which they are found. There is thus virtually nothing to favour a lightning mode of origin for any of the groups of the true tektites.

SUGGESTION OF TERRESTRIAL ORIGIN ON THE BASIS OF TRACE ELEMENT COMPARISONS.

The fact that the amounts of trace elements in tektites are about the same as in the lithosphere, has been used as evidence to support terrestrial hypotheses of tektite origin (Heide, 1936). There is no proof, however, that small amounts of trace elements are confined solely to the earth's lithosphere. Similar small amounts of trace elements may well occur on known or unknown heavenly bodies of a type from which tektites may have been generated. In fact, recent advances in cosmological investigations suggest that the abundance-ratios of the elements, apart from such light elements as hydrogen and helium, are essentially the same throughout the universe, thus further discounting the similarity to the lithosphere abundance-ratios as evidence of the terrestrial origin of tektites.

Chapter IX.

THE ORIGIN OF TEKTITES.

THEORIES OF EXTRATERRESTRIAL ORIGIN.

Although receiving little support at the time, theories relating to the possible extraterrestrial origin of tektites had started to evolve towards the close of the nineteenth century, with the suggestion that billitonites and possibly australites were blobs thrown out from the volcanoes of the moon (Verbeek; Twelvetrees, 1897). It was believed that Landerer's determination of the polarization angle of the moon (33° 17′), suggested that it had a glassy surface from which tektites, which possess a similar polarization angle, could be derived. This theory has been regarded as one of the first definite steps towards a rational explanation of tektite origin. It was thought to be an unlikely mode of origin by some authors (P. G. Krausé, 1898; Oswald, 1936), and Krausé suggested that the tektites were developed from a body that rarely approached the earth, and was later lost again from the solar system. On the other hand, some authors accepted the lunar volcanic theory as not so improbable if the huge lunar explosion craters were taken into account (Linck, 1924, 1926, 1928), and if it was considered that it was only necessary for a projectile to have an initial velocity of 2,100 metres/sec. to leave the moon's sphere of attraction. Other calculations are that the velocity of escape from the moon need only be 1½ miles/sec. (approximately 2,400 metres/sec.) as compared with 6·94 miles/sec. to escape from the earth (Mason, 1930). The chance of such projectiles reaching the earth from the moon, is considerable, determined as 1 in 14,000 by Dr. O. Knopf of Jena (see Linck, 1926a). As an outcome of these deliberations, tektites were regarded as all belonging to one definite geological epoch, and so they were projected earthwards at a time when the moon was in a state of eruptivity and the earth was younger.

However, this theory requires all tektites to belong to one and the same geological epoch, at a time when the moon was in a state of eruptivity, and it has already been shown (see Chapter VII) that tektites occur in strata of different geological ages, and that none of the tektite groups are older than Mesozoic. On the other hand, astronomical evidence is that the earth-moon system is quite an old one, astronomically and geologically, as evidenced by the coincidence of the moon's rotation period and orbital period. Then again, the moon could not have been hot enough to be erupting freely in Mesozoic times and as cold as it appears to be at the present time, for if the available evidence is to be trusted, the moon probably cooled much more quickly than did the earth. Moreover, if tektites were erupted by the moon at an astronomically (and geologically) very early period, as some writers believe that meteorites were, there is then no reason why their fall should be confined to certain geological periods or to certain terrestrial regions.

The moon has also been pictured as an " adopted offspring " or a residual of a destroyed planet duly captured by the earth, which had a different composition to that of the earth, and a greater volume of clastic sediments that became molten on explosion of the destroyed planet (Linck, 1926a). The tektites were thus supposed to be part of such sediments, and these had been forced to encircle the sun, after the planet broke up. Near the sun, they melted, their surfaces boiled, giving rise to the peculiar corroded surfaces. Smaller pieces melted entirely and became free of gas. On slow movement away from the sun, crystallization set in (cf. crystal-bearing (?)tektites from Macusani and

Paucartambo, Peru). During subsequent fall to the earth, only exterior melting and secondary fusion of some included crystals occurred. On the basis of these ideas, which were considered to satisfactorily explain all the peculiar relationships of tektites, it was thought unnecessary to group tektites with meteorites, because they have a distinctive sculpture, are of sporadic occurrence, and have a different chemical composition to that of stony and metallic meteorites.

Other theories involving the moon as a source of tektites are based on the idea that the moon broke away from the earth by fissional separation, leaving the Pacific Basin as a huge scar on the earth's surface. Such a theory was admitted as being presented " with all the distrust that everything not a result of observation or calculation ought to inspire " (Rufus, 1940). Some of the fragments left behind during separation, were thought to have acted as a swarm of tiny satellites, with a rotation period around the earth, within the *Roche Limit**, and coinciding with the earth's period of rotation. The tiny satellites remained suspended over the Pacific Basin for a considerable time. Gravitational attraction ultimately caused them to fall to the earth as tektites. The David—de Boer and the Lacroix—Spencer Great Circles lay directly below the orbits of the chief swarms of these satellites. This theory was deemed to account for the uniform composition and great abundance of tektites in south-east Asia, the islands to the east and Australia. Owing to cumulative perturbations caused by retardation by the moon, it was believed that the glassy objects would thus fall to earth in widely separated geological epochs.

The origin and nature of australites were formerly regarded (Beyer, 1940) as fitting in best, among the tektites, with Rufus' theory. A strong objection to this hypothesis is based on the matter of chemical composition. Fissional separation leaving the Pacific scar, necessitated the supposition that the tektites consisted of glassy basalt or tachylyte, derived from a deep crustal layer of the earth. Tektites have far too acidic a composition to be bracketed with glassy basalt.

Another theory of tektite origin from the moon, the Lunar Impact hypothesis (Nininger, 1940, p. 1936 and 1943), pictures bombardment of the moon by meteorites, causing violent splashes of lunar rock (" lunite ") to be projected upwards at velocities sufficiently great for them to pass beyond the moon's gravitational control. Under the terms of this theory, the absence of a lunar atmosphere would allow ejectamenta to leave the moon at velocities greater than the minimum velocity of escape from the satellite, and enter that of the earth, reaching it in the form of tektites.

Objections have been raised to the Lunar Impact hypothesis on the grounds that with the continued fall of meteorites on the moon, tektites should still continue to fall on the earth, and be distributed at random over its surface, instead of being located along a small number of Great Circles (La Paz, 1944, p. 139).

On the other hand, the hypothesis that tektites originated on the moon, is regarded in some quarters (Kuiper, 1954, pp. 1101-1102) as being able to account (i) for the low age of tektites (in the order of 10^6 years or less, as determined by H. E. Suess (1951) from the A^{40}/K^{40} ratio, (ii) for the fact that the bubbles in tektites have pressures not exceeding 1 mm. Hg. (a value approximately required

* *Roche Limit* = the distance from a planet's centre, within which a satellite cannot remain without danger of disruption. This distance is about 2·44 times as great as the radius of the planet.

to uphold the bubble against the surface tension of the liquid melt), (iii) for the fact that they occurred in showers, and (iv) for their very special composition (not matched or even approached by meteorites and suggesting a fractionation process requiring a high temperature). On the grounds that it is dynamically possible, the suggestion has been advanced (Kuiper, 1953, p. 1158) that tektites might consist of silicate material expelled from the earth by the evaporation of an appreciable fraction from its molten surface during a period of highest central temperature. Such material moved out into interplanetary space, acquired a circumsolar orbit, and became remolten and degassed during close approach to the sun prior to ultimate collision with the earth.

Such a theory is admitted as being at present without any direct confirmation (Kuiper, 1954), and it has been shown (Urey, 1955, p. 28) that the tektite swarms could not have been moving in circumsolar orbits. To do so, the swarms would have to possess density of 10^{-6} gm./cm^3 or more, in order not to have been scattered by the sun's gravitational field. If the swarms did possess this density, and the widespread distribution such as shown by the australites is taken into account, then the tektites would fall with a surface density of around 100 gm./cm^3 (i.e., 10^{-6} gm./cm^3 times 10^8 cm.), which Urey states is definitely not observed. Hence the source of the tektites would have to be nearer the earth—possibly the moon being the source. If so, however, the chemistry of the tektites is such as to require most unusual assumptions concerning moon history, if tektitic material is to be considered as being produced thereon, and so it has been concluded (Urey, 1955) that tektite origin from the moon seems to be an impossible one, from purely astronomical arguments, and that they are therefore most reasonably to be regarded as terrestrial in origin.

SUGGESTIONS OF TEKTITE DERIVATION FROM OTHER HEAVENLY BODIES.

The tektites from Czechoslovakia, Billiton Island, and Australia have been suggested to originate from a swarm of small meteorites produced on the breaking up of a larger *kosmolite* of granitic character, by collision with other bodies such as *cometoids* (Goldschmidt, 1921, 1924). The *kosmolite*, regarded as being composed of acid rocks, melted and scattered molten silicates as a shower of glass drops ("himmelgläser") that rapidly hardened into tektites in the cold of space.

Tektites have also been considered to represent fragments of a satellite called X_3, which fell to earth in Tertiary times (Belot, 1933). The Philippine tektites were thought to have formed within the solar system, rather than in an interstellar environment (Winderlich, 1940). The theory that tektites represent the "sial" granitic zone of a disrupted planetoid, while siderites and aerolites originated in the "nife" and "sima" zones respectively of this planetoid, has received support from some authors (e.g., Denaeyer, 1944).

Without suggesting a source, Van der Veen expressed the opinion that a sizable mass of glass entered the earth's atmosphere and became fluid from the effects of air resistance. Escaping gases caused bursting into drops, or, when the liquid was highly viscous, into more irregular bodies.

In discussing the chemical and petrological nature of the earth's crust, tektites have been pictured as representing fragments of an original glassy skin, developed at the time of consolidation of a cosmic body on which, because of its small mass, no atmosphere was present, so that the skin was not lost by erosion

on the surface (Washington and Adams, in Gutenberg, 1951, p. 95). The mechanism whereby this glassy skin formed into tektites as we know them, was not suggested.

A lost planet originally located between the orbits of Mars and Jupiter, and having a size approximately that of the earth with generally similar physical and chemical characteristics, is required for the formation of tektites according to Stair (1956, p. 409). A nickel-iron core surrounded by troilite and olivine topped with the glassy silicates and glasses is pictured, with the glasses uppermost. The fusion temperature, striae, strain, inhomogeneity, &c., of tektite glass produced from the glasses on or near the surface of this planet, all call for a forming temperature of between approximately 1,500°C. and 2,500°C. Such glasses are considered as not being producible as flash products by collision or short-period heating by other means. The temperature was not high enough to vaporize certain components retained in the glass, and the period of heating was long enough for the different materials composing the glass to fuse properly and mix into a more or less homogeneous glass product. The general character of all the tektites indicates incomplete mixing, as is to be expected under the conditions where new materials are being constantly added to the glass batch. The fact that certain of the alkalies remain is regarded as an important consideration in any study of the temperature conditions under which the tektites were formed. The presence of oxygen in combination with the various metals forming the basic structure of the glass, serves as conclusive evidence of the existence of considerable amounts of oxygen on the lost planet at the time of tektite glass formation.

Although Barnes (1940a) originally considered that tektites might have had a mode of origin by lightning fusion of terrestrial materials, he subsequently (1951) concluded that the " two periods of fusion " exhibited by australites, were incompatible with a terrestrial origin, and an origin was suggested from a celestial body, destroyed by collision, which contained sedimentary and other rocks similar to those on the earth.

An origin of tektites from comets has recently been suggested (H. E. Suess, 1951, p. 79), in which Dr. H. Urey has drawn attention to the fact that comparatively volatile matter could be expected to have accumulated in the comets, the main constituents of which are ice and frozen ammonia. When close to the sun, the ice and frozen ammonia of the comets may have completely evaporated, and if the distance from the sun was small enough, silicates remaining in these comets might have been melted to form a cloud of small objects (tektites) which occasionally may reach the earth's surface. It was calculated by Dr. G. Kuiper (see H. E. Suess, 1951, p. 79) from the average number of comets passing the sun, that from the astronomical aspect, the probability of the molten fragments from comets forming a swarm of tektites that fell to earth, was once in a few million years. Such an assumption does not necessarily seem to be contradicted by the isotopic composition of the oxygen in tektites as determined by Silverman (1951). The O^{18} content of tektitic oxygen is noticeably higher than that of stony meteorites and igneous rocks, and is within the range of that of sedimentary rocks. This is explained (H. E. Suess, 1951) by assuming that O^{18} was exchanged in the direction of equilibrium between the water and the oxides during the process of heating and evaporation of the comet. The probability of the idea of there being a genetic relationship between tektites and comets, which is not a new one, is thought by some to be rather greater than that of the numerous other theories of tektite origin. Before this theory is accepted,

it becomes necessary to advance an explanation for the development of the lechatelierite particles in tektites, in terms of an ice—frozen ammonia—silicate comet. Is it to be expected that the silica in such comets, can be in the form of quartz grains or other anhydrous silica requisite for the formation of the lechatelierite particles? Moreover, how can the gas content of tektites (largely CO, CO_2 and H_2) be explained on this hypothesis? Then again, it would be essential to have all the ammonia completely disposed of, for it has not yet been detected in any of the known tektites.

The theory that tektites represent earth material propelled in all directions as a consequence of cometary collision (Urey, 1957)—a phenomenon which is expected to occur about once every fifty million years, does not satisfactorily take account of the fact that the tektite groups found in different parts of the world, fit into different periods of earth history within the compass of one fifty-million-year span. Several of the known tektite groups are thought to have been formed in the Pleistocene, to accord with this theory. However, the work of several observers has resulted in the conclusions that Ivory Coast tektites are possibly late Mesozoic, while bediasites are Eocene, moldavites Middle Miocene, indomalaysianites Middle Pliocene, javaites Middle Pleistocene, rizalites early part of the Late Pleistocene, and australites Post-Pleistocene to Early Recent. The majority of these groups of tektites could not therefore be accounted for by the suppositions (Urey, 1957, p. 577) that only one cometary collision in 50 million years is required, and that such a comet broke up into separate masses which fell simultaneously at widely separated points to form many of the various groups of tektites in Pleistocene times. No two major groups of the tektites can be positively shown to be of identical geological age. Urey (1957, p. 556) has calculated that tektites could not arrive as a swarm, because a swarm would be required to have a diameter of 10^{8} cm. and a density greater than 10^{-6} gm. $cm.^{-3}$, and should thus pile up the tektites to a depth of 100 gm. $cm.^{-2}$ over southern Australia—a condition which is not observed. Urey adds that he knows of no answer to these arguments. Perhaps the answer is to be obtained from a consideration of the very extensive degrees of ablation to which australites must have been subjected during the phase of atmospheric traverse at greater than ordinary supersonic velocities. The majority of the known australite shapes, represent secondarily modified primary shapes; the greater proportion of them lost from 65 per cent. to 80 per cent. of their bulk by ablation and fusion stripping, and many others were completely lost by total evaporation during passage through the atmosphere at very great speeds. Here, then, is a sound means of very effectively reducing the total bulk of a swarm of australites to at least a quarter of the original, during the period of initial entry into the atmosphere and final landing on earth's surface. Hence there is no necessity to postulate piling up of tektites over southern Australia, to the extent suggested, and the objection to the arrival of australites on earth as a swarm, is thus eliminated.

An autotektic (= self-melting) meteorite planet, which may have disrupted relatively recently, has been suggested as a source of tektites (Cassidy, 1956, p. 426), self-melting resulting from heating-up by radioactive materials segregated in an acidic crust, disruption resulting from gravitational perturbations. The process of disruption suggested in this theory, would have to be capable of generating millions of small spheres, spheroids, dumbbells, and apioids of revolution in the proportion of approximately 80 per cent. spheres, and the remainder elongated forms of extraterrestrial glass, to satisfy the demands of the australite population and other tektite types. Several disruptions would be

necessary to account for the different times of arrival of the various tektite groups on earth surface. Formation of such primary shapes during disruption, would need to be relatively rapid to account for the nature of these shapes as based on studies of the secondary shapes of australites, and the disruptions would have to be of such a nature as to create the very many small-size objects of glass with their internal and external flow patterns, without causing volatilization of their normally readily vapourized alkali content. If these, and other, tektite characteristics can be fitted into an autotektic, disrupted meteorite planet theory of origin, it would become necessary to regard the acidic crust as approaching a charnockite (hypersthene granite) in composition. Tektites and charnockites contain much the same silica, alumina and iron contents, although the ratios of FeO to Fe_2O_3 are a little different; the lime and magnesia contents are higher in the tektites, potash and soda lower, compared with charnockites.

SUGGESTION OF DERIVATION OF TEKTITES FROM SOLAR PROMINENCES.

Tektites have been related hypothetically with palaeoclimatology and astrophysics (Himpel, 1938), by advocating that ice ages could be attributed to a periodic variability of the sun, and a period of maximum activity produced more intense commotion and aqueous precipitation in the earth's atmosphere. During this period, nebulous material was pictured as being projected by the solar prominences. On reaching the earth's atmosphere, the larger part of the projection, made up of hydrogen, gave rise to clouds, the remainder produced tektites. Himpel recommended that geologists search for tektites in Carboniferous glacial deposits. The theory was advanced partly on the false assumptions that all known tektites belonged to the Quaternary Ice Age, and are all identical in composition. There are no records of tektites occurring in late Palaeozoic glacial deposits, or in any glacial deposits whatsoever for that matter.

METEORITE OXIDATION THEORIES.

The theory that tektites were formed by combustion during the passage of meteorites through the earth's atmosphere, was supported by the foremost authorities on tektites, some twenty or more years ago (Lacroix, 1932; F. E. Suess, 1932), but the hypothesis appeared quite artificial to others (Watson, 1935).

The meteorites were considered to consist largely of the lighter metals—Al, Ca, Na and K—and of silicon. Considerable friction and violent oxidation caused vitreous tektites to develop from meteorites of this postulated but unproven composition. The ideas involved in the meteorite oxidation theory were evidently based on the somewhat divergent theories of cosmic origin advanced a few years earlier (Michel, 1922; Goldschmidt, 1924), in which tektites were regarded as forming by oxidation in the earth's atmosphere of the diffuse matter composing the tails of comets. Later, it was advocated that tektites could only be of meteoritic origin (Michel, 1939) and that the material composing them entered the earth's atmosphere, either as glass from a " glass sea " on some other celestial body, or as light metals that produced glass on oxidation within the earth's atmosphere.

Disagreement was expressed (Linck, 1928, p. 229) with the earlier suggestions concerning tektite development by oxidation in the atmosphere of the diffuse matter contained in the tails of comets, because it was thought the theory relied too much on supposition and neglected too much the known facts

concerning tektites, but other authors (Beyer, 1934; Fenner, 1938b, p. 209) were virtually in complete accord with the theory of development from meteoritic oxidation within the atmosphere.

Lacroix' views required tektite formation from " microsideritic holometallites " made up of silicon and light metals unstable in the presence of oxygen. The tektites were regarded as " spatters " from violent oxidation at high temperatures of this type of meteorite. It has been pointed out (Barnes, 1940a, p. 554) that the introduction of " microsideritic holometallite " is really unnecessary, that this is a purely hypothetical type of meteorite that has never yet been observed, and that it has been postulated on the insecure basis of tektites being meteorites. Moreover, it will be shown later that tektites such as the australites, were most probably introduced into the earth's atmosphere as cold bodies. Nevertheless, it has been argued (Lacroix, 1932) that if tektites, like meteorites, had wandered through cold interplanetary space, they should have arrived in our atmosphere as broken lumps deprived of individual forms, and because of their physical state, they were not consolidated in the same extraterrestrial regions as meteorites, but were small masses with forms developed by fusion. Opinions differ on this matter.

Among the earlier, more rational opinions of the origin of moldavites, these tektites were described as consisting of glass on first entering the earth's atmosphere (F. E. Suess, 1900, 1909), it being considered that the absence of water from tektites and their higher magnesium and iron content relative to alkalies, favoured a meteoritic origin (F. E. Suess, 1914). Subsequently, however, for australites in particular, F. E. Suess (1932, 1935, and in Fenner, 1935a, p. 140) imagined that a large meteoritic body of readily combustible, unoxidized metal (calcium, magnesium or aluminium as in shooting stars), could take fire on entering the atmosphere. The casual silica content burst into a million molten glass drops that acquired characteristic shapes while spinning earthwards. Other tektites were thought to develop in like manner, but the glass composing them was considered to be more viscous, so they fell as more compact, slaggy lumps that broke down to angular fragments while lying on the ground. Further elaborations of this idea (Fenner, 1938b, p. 209) pictured a widespread swarm of combustible meteorites weighing 30 to 300 tons, and containing 10 per cent. siliceous material, that visited the earth at a time " geologically recent but historically remote ". The passage of the swarm on a wide, irregular front of 1,000 miles at a height of 80 miles above the earth's surface, was considered to last between 45 seconds and 5 minutes. The burning meteorites shed incombustible material as molten silica blobs averaging 3 grams weight, in all directions. These sped earthwards in 3 to 6 seconds, each rapidly rotating and undergoing ablation, becoming chilled into the solid state during the last portion of flight.

To explain the provincial distribution of australites according to their chemical compositions, it was later suggested (Baker and Forster, 1943, p. 398) that an extraterrestrial body from which glassy meteorites were discharged, exploded at various intervals during its trans-Australian traverse, progressively ejecting material of slightly different composition and specific gravity. On this basis, composition variations would arise from small differences in the duration of burning in the atmosphere. The first explosion over the continent would form australites with more volatiles than would later explosions, due to longer periods of burning between the first and the last explosions. It has since become evident, however, that australites must have entered the earth's atmosphere from outer

space as cold bodies, and evidence has been accumulated to indicate that australites did not necessarily rotate during their passage through the atmosphere (see Chapter X).

Other evidence has been brought to light which nullifies the theory of tektite origin by means of meteorite oxidation within the earth's atmosphere. One objection (Spencer, 1937b, p. 504) is that " such a burning would surely cause the dispersal of the matter in a fiery trail ". On this basis australites should be found on the earth's surface distributed in a long, narrow zone, hence Fenner's introduction of a whole swarm of light-metal meteorites advancing on a wide front 1,000 miles across. Then again, if tektites originated from a combustible light-metal meteorite composed of elemental silicon, sodium, magnesium and such easily oxidizable elements, difficulty arises in explaining the presence of the lechatelierite particles found in tektites. For these particles to occur in tektites, quartz particles would have to be present in the parent source material, and the meteorite oxidation theory advocates elemental silicon. At the temperatures attained by oxidation of the hypothetical, burning light-metal meteorite, most and probably all of the silica content would be volatilized. It has been shown by experiments carried out in the University of Melbourne Geological Laboratories, that australite glass very rapidly vaporizes in carbon arc fusion tests. Under conditions of burning therefore, it is more than likely that any silica present would disappear, and consequently temperatures developed during a " burning " process are probably too high for tektite glass formation with their residual content of small lechatelierite particles.

Other pieces of evidence discount entirely the mode of origin of tektites by meteorite oxidation. It has been shown that two serious objections to the " Oxidation Hypothesis " are based on the amount of oxygen required for combustion in the limited time of flight and on the behaviour of iron meteorites in falling (Paneth, 1940; Campbell Smith and Hey, 1952b). The fact is that rapid flight through the atmosphere would be far too short for reaction with the enormous volume of oxygen that would be required, and the mechanism of such a chemical reaction during flight through a resisting medium, becomes entirely incomprehensible. The evidence shows that the material fused from stony and metallic meteorites by frictional heat, becomes immediately swept away and dissipated as dust. There is thus no reason why a hypothetical light-metal meteorite should behave otherwise and produce blebs of fused glass.

Furthermore, in considering the question of the cosmo-chemical process of the separation of tektitic matter from original solar or meteoritic material, it has been shown from the thermodynamic properties of silicon and aluminium and their relevant compounds, (which are the main constituents of tektites), that these elements will not condense in the elementary state from solar matter under any thermodynamic conditions. The difficulty thus arises to comprehend how a meteorite with elemental silicon and aluminium could be developed from any kind of cosmic matter, and then shed tektites while burning its way through the earth's atmosphere (H. E. Suess, 1951, p. 78). The main components of tektites, the Si and Al, are the most volatile of the compounds present in the silicate phase of ordinary meteorites, while relative to cosmic matter, the tektites are enriched in the minor constituents having higher vapour pressures. H. E. Suess (1951, p. 79), thus assumes some sort of distillation process during the formation of meteorites or the terrestrial planets, with tektitic matter separating from the condensing material.

SUGGESTED ORIGIN OF TEKTITES AS PLASTIC SWEEPINGS OF METEORITES.

Whereas some tektites, such as the moldavites, have been regarded as being derived from a single meteoritic mass estimated to weigh 100 tons, and subjected to sufficient air pressures (1·56 to 2 kilos./sec.) whereby molten drops were separated from the meteorite, (Hanus, 1928), australites on the other hand have been suggested to originate as "plastic sweepings" from a meteorite (Hardcastle, 1926). Such a theory is based on the knowledge that some newly fallen stony meteorites have a thin skin of fused glass. Fusion was due to heat generated by a meteorite travelling at a cosmic velocity of several miles a second through resisting air. The glass skin would not represent the total glass produced during aerial flight, and any viscid glass formed by general surface melting would be swept off in considerable quantities. The individual sweepings had a small amount of translational energy when torn off their parent meteorite, were quickly pulled up by the resisting air, quickly chilled and solidified by radiation. Then they descended to earth at moderate velocity. The detailed structures of australites were regarded as proof of their origin as plastic sweepings. The parent meteorite was pictured as being of large dimensions; it swept through the atmosphere at high velocity, and during east to west flight across 2,000 miles of Australia, it lost countless fragments that fell to earth as australites. East to west transit was advocated because the heavier "bungs" without fine sculpturing, occur mainly in Western Australia, where buttons are scarce and flow rims on lensoids narrow.

Among the chief criticisms of this theory is the objection that the parent meteorite must have been of extraordinarily abnormal composition, and of a type so far unrecorded upon the earth's surface. Moreover, recent examinations of the internal structure, shape, dimensions and radii of curvature of the posterior and anterior surfaces of a number of excellently preserved specimens of australites, all point to the greater probability of these tektites having been formed as independent bodies in an extraterrestrial birthplace, and subsequently modified during secondary frontal fusion on rapid flight earthwards through the atmosphere (see Chapter X). Then again, on the basis of Hardcastle's hypothesis, the front surfaces of australites should be the most pitted, whereas in actual fact, the rear surfaces are most pitted. The hypothesis of origin in the earth's atmosphere as plastic sweepings from meteorites, cannot be accepted on these grounds.

METEORITE SPLASH THEORY.

Tektites have been regarded in some quarters as the by-products of the impact of large meteorites with the earth's surface. Heat of impact is supposed to have fused and altered the sediments at the point of meteoritic impact (Spencer, 1933a, p. 117). Accompanying gaseous explosions caused "bombs" and droplets of molten silica to splash outwards from meteorite craters, and solidify as tektites.

This hypothesis applies satisfactorily to the formation of natural silica glass found associated with meteorites and meteorite craters, but there is a great weight of evidence against the application of the theory to the development of tektites.

Several authors believed that Spencer's Meteorite Splash Theory was the best yet advanced to explain tektite origin (Scrivenor, 1933), and that it offered the most serious challenge to theories of extraterrestrial origin (Barnes, 1940a,

p. 483). Scrivenor leaned towards the theory because he thought the occurrence of metallic spheres in tektites from Indo-China and in Darwin Glass, resembled the metallic spheres in meteorite crater glass from Wabar, Arabia, where the glass is known to be due to fusion of sediments by heat of meteoritic impact or accompanying gas explosion. However, it is very doubtful, in the first place, whether Darwin Glass, is a true tektite, and F. E. Suess regarded Darwin Glass as the only occurrence for which Spencer's Splash Theory would not have to be rejected immediately, because of its very limited extent compared with the distribution of all other known tektites. The chemical and physical dissimilarities between Darwin Glass and tektites, have resulted in most authors agreeing to its removal from the group of true tektites, and its placement in the same category as meteorite crater glass. Reasons are set out in Chapter XVI, of this monograph, for doubting both the suggested tektitic character and the postulated meteor crater glass origin of Darwin Glass. In the second place, nickel, a characteristic component of most examples of meteor crater glass, is generally absent, or present in only minute traces in tektites. Some natural glasses associated with meteor craters, e.g., Wabar (Arabia), Henbury (Central Australia), Campo del Cielo (Argentina), Odessa (Texas) and Canyon Diablo (Arizona), contain small spheres of nickel-iron, but none have been found in the Aouelloul glass from Adrar, western Sahara. Spencer thought a test for nickel in australites would help decide whether they are aerial fulgurites or due to meteoritic splash. Minute amounts of nickel detected spectrographically by A. J. Gaskin (Baker and Gaskin, 1946), in an australite from Mulka in South Australia, are too small to confirm Spencer's Meteorite Splash theory in its application to australites. Furthermore, it has been shown by spectrum analysis of a moldavite (Preuss, 1934, p. 480), that the recorded amounts of 0·01 per cent. of Cr_2O_3 and 0·002 per cent. of NiO, do not support the theory that tektites had any relation with meteorite craters.

Other objections to the theory have been put forward. It was thought that one of the strongest arguments against the Meteorite Splash Theory of tektite origin, was the fact that no tektite has yet been described containing partially fused rock or sand (Scrivenor, 1933, p. 678). Some adhering, partially fused constituents would be expected on tektite exteriors, if all had been derived by meteorite splash. Of many thousands of australites examined, none show such phenomena, and the lechatelierite particle content would not necessarily support an origin as a meteorite crater glass.

Other criticisms of the Splash Theory hinge mainly upon the fact that tektites occur over an infinitely wider area than is occupied by meteorite craters, and they are seldom found in the neighbourhood of the right kind of rocks to yield such a fused product. Spencer's reply to this criticism is that the local distribution of tektites must be considered in connection with recent and ancient drainage systems, but he admitted that the peculiar forms and the wide distribution of the australites, presented difficulties.

It has been considered that the Meteorite Splash Theory could not apply to such large tektite deposits as moldavites and indochinites, especially as moldavites are totally unrelated to sub-surface materials where they occur (Rosicky, 1935). Then again, the theory was thought to be hardly tenable for rizalites, australites, &c., because the widespread and consistent nature of the Austro-Indomalaysian tektites were only susceptible of explanation by means of " a single, uniform cause, capable of simultaneously operating over a vast area " (Beyer, 1934).

It is thus seen that the Meteorite Splash Theory of tektite origin has little or nothing in its favour, and the main factors that seem fatal to the theory are (i) the large areas of distribution of tektites generally, and (ii) the peculiar chemical composition of the glass of tektites, which is not equal to any likely rock plus any known types of meteorites, stony or glassy.

"CONTRATERRENE" METEORITE IMPACT THEORY.

The production of atom bomb explosions in recent years, and the formation or fused silica debris as a result of these explosions, has resulted in the suggestion that a study of the fused silica debris might solve the problem of tektites and support the hypothesis of "contraterrene" meteorite impact (Khan, 1947, p. 35).

In the terms of this theory, theoretically eonceivable "contraterrene" meteoritic impact could only be "detected" from explosions caused by sudden annihilation of "contraterrene" matter (whether as comet or meteorite) when it comes into contact with terrene matter. Atomic bomb explosions are the only known phenomena that could provide sufficiently close comparison to the effects resulting from "contraterrene" meteoritic impact. Reported temperatures of atomic explosions are as high as those within stars, so that artificial transmutation of elements, generally from lower to higher atomic weights result, also strong radioactivity and gamma-ray emission. It was thought that any general agreement between the physical and chemical properties of atom bomb silica glass and tektites or natural silica glass, might cause some of the mystery surrounding tektite origin to disappear and provide "contraterrene" matter with something "of an objective reality."

Although the "contraterrene" meteoritic impact theory might be thought capable of solving the mystery relating to some features and aspects of tektites, the theory is nevertheless a fantastic one, and has not been taken seriously by authors on tektites. Strong objections, similar to those already raised against Spencer's Meteoritic Splash Theory, also apply to the "Contraterrene" Impact Theory." Certain peculiarities such as shape of australites, composition and distribution, &c., of the different types of tektites, would still remain difficult of interpretation. For australites in particular, with their distribution over 2,000,000 square miles of country, very many "contraterrene" impacts are needed, and these would somehow or other have to produce a chemical gradient in australite composition across 2,000 miles of the continent, in order to give rise to the known provincial distribution of australites. Moreover, the widely variant terrene matter in widely dispersed localities, that would become affected by such "contraterrene" explosions, would surely have to yield end products of more widely divergent chemical compositions than are actually met with among the known, accepted true tektite groups. Furthermore, the requirements of such a large number of "contraterrene" explosions to attempt to explain such a wide distribution of australites, would surely in themselves, have had far-reaching, disastrous effects. Then again, there is no known evidence whatsoever of "contraterrene" matter.

GREAT CIRCLE THEORY OF METEORITIC ORIGIN OF TEKTITES.

The Great Circle Theory, advanced initially by David, Summers and Ampt (1927, p. 181), was an attempt to account for the distribution of tektites known to 1927, and was based on the idea of a meteoritie origin. Five separate occurrences of natural glass, all referred to the tektite group at that time, were considered as belonging to one and the same group of meteorites. These five

occurrences known to 1927, were Darwin Glass, australites, billitonites, moldavites and schönite, all lying on the earth's surface along the same great circle or in a zone 10° on either side (fig. 29).

These occurrences were thought of as discrete swarms of small meteorites, or the scorification products of larger, separate meteoritic bodies that became disrupted during passage through the atmosphere. As the swarm approached

FIGURE 29.—Stereographic projection of the Western Hemisphere, showing location of tektites and supposed tektites on the Great Circle Theory, with a belt 10° wide on each side of the David-de Boer Great Circle.

A—schönite.
B—moldavites.
C—billitonites.
D—australites.
E—Darwin Glass.
(After David, Summers and Ampt, 1927.)

the earth, it became so much elongated that a ring of acid meteorites disrupted into a vanguard and a rearguard. The vanguard was supposed to fall in Tasmania as Darwin Glass, the rearguard in Europe as moldavites. The main body over Northern Tasmania, Australia and the Netherlands East Indies, formed australites and billitonites.

The Great Circle Theory received some support from certain authors. It was used by Lacroix (1932), as a working hypothesis, but he considered it was necessary to prove there had been a synchronous fall of tektites to prove the theory correct. Later, uncertainty was expressed by Lacroix (1934), that tektites were all of the same age or that they all resulted from a single phenomenon, with the additional objection that the tektites of Ivory Coast, West Africa, did not fit into the Great Circle scheme.

The band-like nature of tektite distribution along a great circle, called the "David-de Boer Great Circle" was regarded as being due to slight oscillations of the earth's equatorial plane about a mean position, and to the width of the stream of cosmic matter impinging on the earth (La Paz, 1938). Several years later, after the discovery of tektite strewnfields off the postulated "David-de Boer Great Circle," it was still considered that the utmost significance must be attached to the fact that millions of individual specimens in the several known tektite deposits, do occur on or near a small number (three) of great circles (La Paz, 1944, p. 141).

The original "David-de Boer Great Circle" has now lost its utility completely. It is fatal to the theory that tektites have been proved to occur in geolcgical strata of different age in earth history (see Chapter VII). Added to this, are the facts that (i) australites are known from Southern as well as Northern Tasmania (see fig. 5), i.e., both north and south of the location of Darwin Glass, which was regarded originally as the acidic vanguard of the disrupted swarm of acid meteorites, (ii) Darwin Glass is certainly not a tektite in the normally accepted sense, and (iii) schönite has been rejected from the tektite group also, having been proved to be an artificial product.

Other authors have concluded that the Great Circle Theory is founded on fallacies (Barnes, 1940a, p. 547), because (*a*) it was still unproven that tektites were really meteorites, (*b*) there was evidence to show that tektites did not all arrive in the same swarm, and (*c*) the additional tektites since found in Africa and North America, are off (40° in Africa) the line or zone of the postulated great circle. Should further tektite discoveries be made in other localities off the zone of the originally postulated great circle, and other great circles are introduced to accommodate them, the result will be, as Barnes remarked, "a meaningless maze of great circles."

TEKTITES AS GLASS METEORITES ON THE EVIDENCE OF THEIR SURFACE SCULPTURE.

The main arguments in favour of a cosmic origin of tektites, were, at the turn of the century, based on the similarity that was thought to exist between the surface sculpture (resulting from corrosion and friction in the earth's atmosphere) of tektites and the surface sculpture of meteorites composed of metal or stone, (F. E. Suess, 1900). The belief in a meteoritic origin for tektites was shown by such factors as their distribution, their mode of occurrence, their shape and general uniformity of composition, together with distinct differences from any known terrestrial glass. At that time, the tektites were pictured as

coming from within our planetary system, originating where water and free oxygen were absent, at a temperature not exceeding 1,500°C. The stages through which all types of meteorites have passed (cf. F. E. Suess, 1932, 1933) are:

(*a*) *astral stage*—meteorite materials were mixed at a high temperature on the surface of a sun-like body.

(*b*) *apostactic stage*—great drops of mixed material were thrown off.

(*c*) *Kathartic stage*—the material of the drops separated into outer slag-like and inner metallic portions.

(*d*) *porotic stage*—solidification set in rapidly enough to cause the formation of chondrules and Widmanstätten figures.

(*e*) *diathraustic stage*—rapid cooling caused disruption.

(*f*) *perihelic stage*—the fragments circulated round the sun, the heat of which, when near thereto, removed the more volatile elements.

(*g*) *atmospheric stage*—they fell as meteorites through the earth's atmosphere, where melting by heat of friction developed fused crusts on the meteorites. In tektites alone, are the results of this final stage preserved.

Objections have been raised to F. E. Suess' ideas that sculpture furnished conclusive evidence of the ultra-terrestrial source of tektites, and the markings on tektites were thought to agree more closely with those on terrestrial obsidian (Merrill, 1911). The fact remains, however, that the mere resemblance of a certain feature on two different objects or sets of objects, is not always a sure criterion that they have had the same mode of origin. It is the other evidence that Suess has drawn attention to, which gives strong support to his postulate of tektite origin as glass meteorites. No matter how the substance of tektites originated, whether by solidification on a heavenly body of comparatively small size, or only during fall through the earth's atmosphere, Suess was sure that this substance had certainly not experienced fractional crystallization under a force of gravity like that of our earth (F. E. Suess, 1932). Tektites solidified from a hot magma, like meteoritic stones and irons, but in their present form, they are probably products of a second solidification, after renewed melting in the earth's atmosphere.

TEKTITE ORIGIN FROM SILICA-RICH GRANITIC BODIES.

In a review of Paneth's 1940 Halley Memorial Lecture (Nature, 1941), it was set out that Paneth accepted F. E. Suess' claim of a meteoritic origin for tektites, on the grounds that hypotheses advocating tektites as products of human manufacture or as terrestrial formations, could easily be disproved, and there was no alternative but to assume a celestial source. In stressing these points, Paneth (1940) used the words of the chemist de Fourcroy, who, when trying to convince his sceptical colleagues of the French Academy of Sciences of the reality of stone meteorites, had said—" by eliminating the absurd or impossible, one finds oneself compelled to adopt what would previously have appeared almost incredible."

Previously, tektites had been considered as remnants of a granitic kosmolite (Goldschmidt, 1921), and as the extraterrestrial homologues of the granitic rocks of the earth's crust (Lacroix), and Paneth suggested that silica-rich granitic bodies, representing original tektite material, entered the *Roche limit* of the sun, and suffered melting and dispersal. Swarms of glass globules formed on cooling, after leaving the perihelion neighbourhood. Because of their high

speed, they would cool down too quickly to crystallise, and in a later encounter with the earth, would be spread over whole continents. On the basis of this theory, all the tektite groups known on the earth's surface would have to be developed at the same time, and they would then have to be precipitated to the earth at the same epoch of the earth's geological history. If, therefore, a theory such as that advocated by Paneth is to be accepted, the process suggested would have to occur more than once during the period of astronomical time coincident with at least the last 60 to 70 million years of earth history, for it is during that time, that tektites are known to have fallen to the earth as showers widely separated in both time and space. Unless such matters as these are taken into consideration, Paneth's theory, which is among the more plausible of meteoritic postulates, would lose its full force. The writer of this monograph believes that development from a silica-rich granitic body postulated by Goldschmidt, by Lacroix and by Paneth, receives some confirmation from the occurrence of the microscopic lechatelierite particles found in tektite glass. As an alternative, the postulated body may have had associated sediments containing clastic grains of quartz, from which the lechatelierite particles may likewise develop. These particles are not products of a crystallization period of the tektites themselves, but represent incompletely fused, partially absorbed particles of silica.

If, as seems most logical, an extraterrestrial source for tektites is to be accepted, it becomes necessary to adopt an origin based partially on Linck's hypothesis (1926a, p. 171), if not in quite the same sense as that hypothesis, and partially on Paneth's hypothesis,—i.e., propulsion from some extraterrestrial body of fused rock having the composition of argillaceous sandstone or arenaceous clay, or else analogous to silica-rich igneous material originally poor in potash and soda, or from which these constituents were lost by subsequent ablation processes. Having been propelled from the sphere of influence of the parent body, the ejected or disrupted material solidified quickly in the cold of outer space. Glass bodies were formed by rapid chilling, with the lechatelierite particles remaining to testify to the original character of the parent rock, taken in conjunction with the composition of the tektite glass, (cf. Barnes, 1940a, p. 506; Baker, 1944, p. 15). The lechatelierite particles prove at least, that tektite glass developed from fusion of rock rich in quartz grains or quartz crystals (i.e., in sediments or in acidic igneous rock). After wandering in space as discrete units, tektites were drawn earthwards. They were already preshaped in their extraterrestrial birthplace, and they entered the earth's atmosphere as cold objects. During atmospheric flight at supersonic velocities, the australites among all the tektites at least, underwent front surface ablation and surface flow, due to heating by atmospheric friction. They did not necessarily rotate through the atmosphere (cf. Chapter X), and their primary internal flow structures had already been determined in a pre-atmospheric stage of their earthward journey. Secondary flow lines developed in the stage of atmospheric flight, are only manifest in thin outer layers of parts of the secondarily formed anterior surfaces of australites, and in the secondarily developed flange structure. Many incompletely absorbed lechatelierite particles in the flange structures of the australites, were swept towards equatorial regions of the developing lenticular australite shapes, and into flanges, there to become drawn out, twisted and contorted by jamming consequent upon the moving in of warmer against cooler glass forming secondarily into the flange structure.

On this basis, the idea incorporated in some theories of australite origin, that these tektites were at one time wholly molten while traversing the earth's atmosphere, can be dismissed, for the above evidence, which in part is elaborated

in further detail in connexion with the development of the shapes of australites (see Chapter X), fits in satisfactorily with ideas relating to gas dynamics under conditions of supersonic flight, whereas, on the other hand, it would appear that aerodynamics are against the probability of liquid or fluid blebs remaining intact during the high speeds of earthward flight to which tektites such as the australites must have been subjected. Under the conditions of high speed flight, it is to be expected that the postulated liquid or fluid globules supposed to represent one stage of australite formation during atmospheric flight, would break up in the atmosphere and be completely dissipated.

Although this explanation may temporarily suffice for the Australian tektites, the same ideas cannot be extended *in toto* to all the other members of the tektite family, for no other member groups possess individuals with the secondary shapes and flange structures akin to those of australites. It may be that the other groups possessed such secondary structures at one time, but being much older than australites as far as their time of arrival on earth is concerned, they could possibly have lost all traces of such secondary features by prolonged erosion. It may be significant that the older tektites such as bediasites for example, show very little in the way of original shapes, while the younger rizalites and some indochinites show a number of forms resembling the primary shapes from which australites were developed, and then the youngest of all, the australites, reveal modified primary shapes (Baker, 1955a, 1956) and, where not yet broken away and destroyed, the astonishingly regular, coiled band of tektite glass that forms a flange in the equatorial regions of most of the different shape types. If an explanation such as this fails to explain the shape differences between the various groups of tektites obtained from different parts of the earth's surface, then recourse must be had to the probability of different speeds of transit through the earth's atmosphere, some moving through the air at sufficiently low speeds to militate against the chances of secondary ablation and sheet fusion developing to any marked degree, others, such as the australites, moving through at far greater speeds, and thus subject to the conditions outlined above. In all the tektite strewnfields, individuals with internal cavities were liable to bursting, possibly by explosion, but more probably by implosion. The causes for this could be impact on landing, provided such examples had sufficiently weak bubble walls, or collapse during flight because of advanced stages of front surface ablation as with the australites, or possibly for other reasons, such as collision during flight or the like.

Whether supporting volcanic, aerial-fulguritic or meteoritic modes of tektite origin, most writers up to now have believed that certain regular forms of the tektites (forms which have not been modified by erosion on the earth's surface), could only form from the passage of a liquid or semi-liquid substance through the earth's atmosphere. Some writers have inferred that the molten glass bodies were revolving during flight, in a plane normal to the direction of propagation (e.g., Fenner, 1934, p. 65; Beyer, 1940). However, it is the author's view that to be in keeping with the idea of tektite origin by expulsion of molten material from an extraterrestrial body, the shapes of many tektites must have resulted at their source, and as a direct consequence of the process of ejection. This applies, assuming that liquid or viscous material was ejected, which is highly probable, but breaks down if tektites are to be regarded as remnants of disruption of an already consolidated glassy body (which probably does not apply). The pre-formed shapes of the tektites, based on origin from ejected liquid or viscid material, must have been maintained while the glassy bodies wandered in space for several million years before being drawn into earth's

sphere of attraction, and such shapes would thus be primary shapes in contradistinction to any secondary shapes resulting from the sculpturing effects of the air during atmospheric flight.

At its best, it is conceded that the theory of meteoritic origin for tektites, as presented above, satisfactorily explains many of the observed facts, although it does not prove beyond doubt that tektites are definitely glass meteorites. The more cautious writers contend that a meteoritic theory should not be accepted in its entirety until a tektite has actually been seen to fall and recovered. However, to be completely convincing even then, an observed fall would only strengthen the meteoritic theory of tektite origin, if witnessed and noted from a clear sky, at a time free of electrical discharges and dust, and in a region far remote from centres of active volcanic eruption. The chances of this state of affairs arising would appear exceptionally remote; in the meantime, consideration of the forms and structures of tektites, especially those of the australites, in the light of recent advances into the realms of supersonic flight, and increased knowledge in the field of gas dynamics at these high speeds of flight, should go a long way towards effectively eliminating all the theories of terrestrial origin for tektites, and providing added support for a meteoritic mode of origin.

Apart from the above arguments and evidence, there are other points in favour of the meteoritic origin of australites. Thus it has been pointed out that antagonists of meteoritic theories of tektite origin have argued that tektites could not be meteorites because their composition is so different from that of all known meteorites; aerolites are basic, for example, whereas tektites are acidic. It is maintained that this argument cuts both ways, and it can be stated with equally as much justification, that since australites did not agree with terrestrial rocks in composition, they are extraterrestrial (Summers, 1909). It has been shown that specific gravity determinations of australites from various localities in the strewnfield, point to a provincial distribution according to chemical composition. Specimens from Hamilton, Victoria in the east were shown to be characteristically more acidic than from Kalgoorlie in the west of the strewnfield (Summers, 1909). Because such a distribution would be impossible by means of volcanoes, water, ice, winds, birds or aborigines, or by electrical discharges fusing dust in the atmosphere, it is contended that a theory of cosmic origin is upheld. Summers' ideas on this score are confirmed by a statistical study of over 1,000 specific gravity determinations of various shape types from many localities in the australite strewnfield (Baker and Forster, 1943, p. 394). Such a distribution over so wide an area, could only be effected by some extraterrestrial process of australite precipitation. All the evidence indicates that such a phenomenon occurred but once over the Australian continent, and at a pre-historic but geologically Recent period. It is not known from aboriginal folklore, whether this phenomenon was witnessed by aboriginal man, although it is highly likely that the Australian aborigine had penetrated as far south as the australite strewnfield, before the arrival of the australites.

Much of the evidence for the meteoritic origin of tektites, may still be regarded as negative evidence, but as Spencer (1937b, p. 503) remarked, since tektites differ from known terrestrial materials, and are found under strange circumstances, it is perhaps natural to assume that tektites have fallen from the sky. It is still conjectural, however, from which part of the heavens tektites originated, but there seems to be no doubt that they came to the earth from an extraterrestrial source.

Using very low background Geiger counting techniques, Ehmann (1957) has detected cosmic-ray-induced radioactivities in certain tektites, and considers that the presence of Al^{26} and Be^{10} radionuclides, which are beta-emitters and relatively long-lived isotopes, is proof of an extraterrestrial origin for the tektites. These radioactivities have been produced while the tektites were in space, and it is assumed that the cosmic-ray flux has remained the same for the last few million years. The Al^{26} and Be^{10} radioactivities are regarded as valuable in the determination of the origin of the tektites, because their half-lives correspond in amount to the period of earth history (late Tertiary to Recent) during which, as indicated by the nature of their geological occurrence, the younger of the groups of tektites appeared upon the earth's surface.

CHAPTER X.

THE ORIGIN AND RELATIONSHIP OF TEKTITE SHAPES.

Of all tektite groups so far discovered, australites have the most strikingly regular forms, with many shape types having flanges normally lacking on practically all specimens from all other tektite groups. The origin of australite shapes has created much more discussion than that of the other groups of tektites. Ideas relating to shape and structure formation are intimately connected with the particular theory of tektite origin favoured by writers attempting to explain these mysterious objects. This part of the tektite problem is thus equally as controversial as theories of tektite origin.

The treatment of shape origin is traced out herein according to the various hypotheses of tektite origin, under the headings:—(1) terrestrial origin—from solid materials; (2) terrestrial origin—generated in a molten state within the atmosphere from terrestrial materials; (3) extraterrestrial origin—fluid or plastic on reaching the earth's atmosphere; (4) extraterrestrial origin—from materials generated in the fluid or plastic state within the atmosphere; (5) extraterrestrial origin—solid on reaching the atmosphere.

(1) SHAPE ON THE BASIS OF TERRESTRIAL ORIGIN, FROM SOLID MATERIALS.

That the shapes of billitonites and of australites were brought about entirely by rolling (van Dijk, 1879; Merrill, 1911), is an absurd postulate, for such a process would have an entirely opposite effect, as observed from the comparison of stream abraded, &c., specimens with unweathered, well-preserved specimens.

Equally as fantastic is the theory of the development of the shapes of billitonites by shrinkage on dehydration of silicate gels (Wing Easton, 1921) and the comparison of the shapes so produced with the perlitic cracks of volcanic glass which delimit spheres, ellipsoids and the like. It is also untenable for australites to have been shaped by the behaviour of a gelmass undergoing desiccation by the sun, and under the control of the shape of the surface of the ground on which rested the postulated stagnant pools that gave rise to the imagined gelmasses (Van Lier, 1933).

(2) SHAPE AS GENERATED IN A MOLTEN STATE WITHIN THE ATMOSPHERE, FROM TERRESTRIAL MATERIALS.

The development of the shapes of australites as a consequence of volcanic activity, has been advocated by several writers since the time of Charles Darwin onwards, most believing that the forms of certain tektites, especially australites, resulted from the rotation of a fluid mass during flight through a gaseous medium. Darwin (1844) thought that since the lip (i.e. = flange) of the specimen he examined was so symmetrical, one had to assume that the "volcanic bomb" (i.e., australite) burst during its rotary course, before being quite solidified, and the "lip" was thus slightly modified and turned inwards. Others also believed that the shape of australites was just that which would be assumed by a small mass of molten, vitreous material falling through the air and rotating as it fell (Spencer and Gillen, 1912).

It has been concluded that the shapes of australites were developed under special circumstances like those which produced Pelée's tears, by rotating of liquid volcanic bodies in the atmosphere (Moore, 1916, p. 52). Pelée's tears

possess primary shapes, australite shapes are those of modified primary shapes of a type that it is considered could not be developed under volcanic conditions, however special, as will be shown further on.

Flat, discoidal australites have been regarded as showing progressive steps by which original glass drops assumed a discoidal form during rapid rotation around an axis at right angles to the plane of the disc (Dunn, 1916, p. 225), and such " flattened drops " were likened to basaltic bombs (Berwerth, 1917). The other shapes of australites, such as buttons, ovals, lenses, dumb-bells, &c., were postulated as having developed from blebs at the bottoms of single and double bubbles of glass blown out from volcanoes (Dunn, 1908b, p. 203, and 1912b, p. 7). It was thought that such perfectly-shaped bodies as the australites could only have formed suspended in a gaseous medium, because they could not assume their shapes in solids, while in liquids such as water, immersion at 1,324°C., their fusion temperature, would reduce them to a powder (Dunn, 1912, p. 4). It has been shown that these ideas are untenable from a physical standpoint (Grant, 1909, p. 445). The forms that a mass of liquid in motion could assume, were proved experimentally to be:—the sphere (possible only with no rotation), the oblate spheroid (stable at low speeds of rotation), the prolate spheroid (stable, if at all, only at high speeds of rotation), the dumb-bell (hourglass) and the apioid (pear- or tear-shaped) figure of revolution. Whereas Dunn regarded the flanges of australites as representing the last flowage of glass down the inside walls of the postulated glass bubble to the edge of the bleb at the base of such bubble, Grant considered they were satisfactorily explained by the action of air on a moving liquid.

No theories have been elaborated to explain the shapes of tektites on the basis of suggestions of tektite origin by lightning fusing dust in the earth's atmosphere, except that the shedding of rings and peripheral flakes from australites, was regarded as being induced by these objects falling into water (Chapman, 1929), after having been formed in the air by electrical discharge.

(3) SHAPE ON THE BASIS OF EXTRATERRESTRIAL ORIGIN, FROM MATERIALS, FLUID OR PLASTIC ON REACHING THE ATMOSPHERE.

Among the earlier views of the origin of the shapes of tektites on the basis of an extraterrestrial origin of the materials composing them, F. E. Suess (1909) advocated that dumb-bell-shaped australites resulted from narrowing in central portions during rotation. In swiftly rotating, long molten bodies or viscous drops, the contents were forced to both ends, resulting in a constricted centre. This would occur in a way similar to that by which Jacobi's Ellipsoids are thought by astronomers to have formed twin stars. Australites generally, were regarded as fairly mobile drops of limited size, while the other tektites were thought to have fallen as more viscous cakes (F. E. Suess, 1932).

The temperature and hence the viscosity of plastic tektite glass, has been regarded as playing a dominant rôle in deciding the ultimate shapes of tektites. The longer forms and sharper sculpturing of Bohemian moldavites were considered as belonging to a slightly later period of separation from a single, large meteorite, compared with the Moravian moldavites (Hanus, 1928). It was concluded that the Bohemian moldavites therefore developed at higher temperatures and lower viscosity, and the Moravian moldavites when temperature was lower and viscosity greater. However, it could also be argued in reverse, that if the swarm of glass bodies reached the earth's atmosphere in a cold state, the Moravian tektites could have had a shorter atmospheric path, and hence

fell in the earlier part of the trajectory. Because they would then have a shorter trajectory, they would have been less heated and remained more viscous, developing less sharp sculpturing.

The Indo-Malaysian tektites have been similarly divided according to the idea that they indicate variable viscosity, and have been grouped thus (Beyer, 1940):

(*a*) *indochinites*—most viscous and represented as long drops.

(*b*) *rizalites*—of intermediate viscosity, and thus occurring as pitted spheroids, ellipsoids and cylindrical forms.

(*c*) *billitonites and malaysianites*—of medium viscosity, represented by deeply etched spheroids and cylinders.

(*d*) *Java tektites*—the least viscous, possessing complex flow lines.

The teardrop- and sphere-shaped indochinites were regarded as eloquently testifying to the establishment of such shapes on small bodies during the fall of sufficiently fluid glass (Lacroix, 1932).

(4) SHAPE ON THE BASIS OF EXTRATERRESTRIAL ORIGIN, FROM MATERIALS GENERATED IN THE FLUID OR PLASTIC STATE IN THE ATMOSPHERE.

Australites have been pictured as spray from a rapidly moving stony meteorite, glass coming from the rear hemisphere of the meteorite, when, by rotation, it was gradually brought within the influence of resisting air (Hardcastle, 1926). As a result of such a process, a rim was supposed to have been produced on each glass drop by momentum of the hinder portion pressing onward against the resisted front. This caused squeezing out of successive concentric or spiral "ripples" in successive shocks of resistance. Irregularly-shaped forms were explained as shreds of stiffer material ripped off the meteorite, and little altered in shape afterwards. It has also been suggested that the "rings" (i.e., flanges) around australites, developed on the least viscous tektites from resistance of the air "which curled up the frontskin as may be observed in smoke rings of guns and trained smokers" (Van der Veen, 1923).

Although, in the writer's opinion, Fenner's (1934; 1935a) earlier views on the origin of the shapes of australites, were substantially correct, he later advocated (1938, p. 198), in order to obviate the criticism of Watson (1935) and Opik (1937), that whatever the manner of tektite origin, it was clear that the glass blobs were generated within the atmosphere in a molten condition. These blobs were supposed to rotate in a plane normal to the flight direction, through the upper air. The failing in this hypothesis is that although the blobs were regarded as already molten, re-heating was supposed to occur by friction of the front and sides of each blob; the rear surface would remain cool, and there would be a backward flowage of material melted from the front surface. For re-heating to occur, there would have to be an intervening cool stage, during the very limited period between the postulated instantaneous formation of molten blobs within the earth's atmosphere, and the onset of the postulated re-heating and partial fusion process. The time taken by tektites to traverse the atmosphere, estimated as three to six seconds, once these postulated blobs were released as independent bodies from their parent within the atmosphere, would be far too short for them to experience transition from a molten stage to a cooling-off stage and then to a re-heating stage prior to final consolidation.

For these reasons, the writer prefers to abandon Fenner's later propositions on shape origin, and places more credence in his earlier postulates, which are set out hereunder.

(5) SHAPE ON THE BASIS OF EXTRATERRESTRIAL ORIGIN, FROM MATERIAL THAT WAS ALREADY SOLID ON REACHING THE EARTH'S ATMOSPHERE.

This section is concerned principally with the origin of the shapes of australites, and the question immediately arises as to whether these tektites traversed the atmosphere with, or without a spinning trajectory. The discussions and suggestions are therefore dealt with below in the two categories (*a*) with a spinning motion, and (*b*) without a spinning motion.

(*a*) *With a Spinning Motion.*

Among the earlier theories on the origin of the shapes of australites, whether these objects were regarded as of terrestrial origin, or whether they were doubtfully thought of as having come to the earth from an extraterrestrial source, there was an element of doubt as to whether they rotated through the atmosphere or not. The outlines of some australites were deduced as coming from spheres, and were referable to the same causes that induced the shape of a drop of water or liquid lead, but although some forms appeared as if due to rotation, it was concluded that all did not necessarily rotate (Stelzner, 1893). Then again, it was doubted whether the well-marked, sharp, concentric flow ridges were entirely due to rotary motion while falling from a great height (Stephens, 1897). The ellipsoidal shapes of some tektites were considered to be consistent with the theory of a long rotary flight, but it was argued that the difference in form of australites was affected by the degree of resistance of the material on which they fell, also by the force of impact. Those falling in river channels would be received just as drops of lead falling from a shot-tower are received in the tank below. Spheroidal or button-shaped drops that fell on mud-banks or soft earth were thought to have been drawn out into ellipsoidal forms while viscous.

Later theories pictured rapid horizontal rotation of plastic material (Walcott, 1898, p. 35), with a tendency to elongation in some forms of the australites, the flowage of material towards the ends of elongated forms being due to centrifugal forces. Additional centrifugal action was thought to cause constriction in central regions of some elongated forms, resulting in two complete, separate bodies. Atmospheric resistance was suggested as being responsible for pushing back the outside of the plastic glass from the advancing side to produce the flange. Shedding of flanges occurred when material was pushed back far enough to cause complete separation. The forms were regarded as being solid on landing, otherwise their symmetry would have been altered if plastic on reaching the ground. Although there are many acceptable points in Walcott's theory, it is considered by the writer that rotation did not necessarily occur, and moreover, it is more than likely that the australites were cold objects on first entering the earth's atmosphere. It is also believed nowadays, in agreement with Walcott, that australites were cold on reaching the surface of the earth. Elsewhere, however, some authors were convinced that tektites such as the rizalites were not completely hardened on landing (Beyer, 1934), because certain spherical forms, " cylinder ends " and others, sometimes showed " a flattened or mushroomed spot of a squashed character " that was thought to have resulted from a soft body of glass striking a hard surface.

Before he was influenced by F. E. Suess' ideas (see Fenner, 1938) that australites were probably generated as molten blobs within the atmosphere, by being shed from a burning light-metal meteorite, Fenner's previous ideas (1934) went a long way towards explaining the origin of the shapes of australites, although, as will be shown later, the writer considers it unnecessary to advocate a spinning trajectory for australites during their passage through the atmosphere. Fenner's earlier theories postulated australite formation in "two atmospheric stages" from glass blobs of various sizes, moving forward through a gas, and rotating rapidly in a plane normal to the direction of movement. Thus, in the formation of a button-shaped australite, the "primary form" was a spherical blob which fused on the forward surface, melting glass flowing backwards to form a flange or rim, thus producing the "secondary form". Much of the anterior surface of the secondary form disappeared by friction, fusion and evaporation. A succession of rims and flanges formed at the equators of the australites, were shed as rings on reaching a certain size. Various forms of australites developed from one another (fig. 30), buttons passing into lens-shaped forms by flange-shedding, and into cores by subsequent equatorial flaking of lenses.

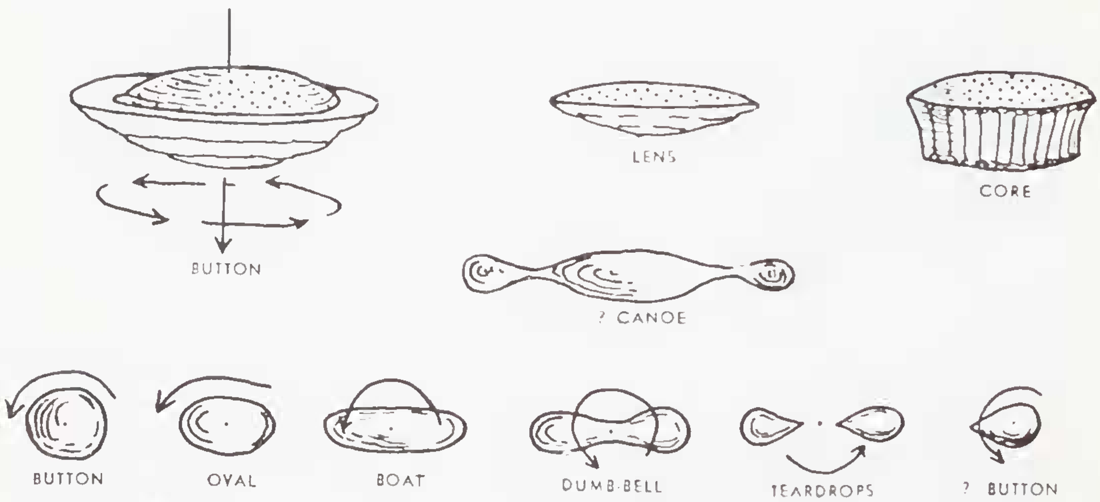

FIGURE 30.- Sketch diagrams showing progressive shape development in australites (after Fenner, 1934).

Up to this point, Fenner's hypothesis appears quite sound, for the australites are evidently regarded as solid objects, being subjected to secondary melting. In further elaborations of shape development, however, the theory becomes hard to follow, because rotating buttons are next pictured as passing by elongation, through the oval and boat to the dumb-bell stage, by constriction in the waist regions to teardrops by separation (fig. 30). On further rotation, these are thought to have possibly passed back to the button stage. Canoe-shaped forms were supposed to have been produced by the development of two constrictions in an elongated, rotating mass. Under these circumstances, it is obvious that the bodies must have been rotating fluid or plastic objects, in order to pass through the various postulated shape stages. It is thus apparent that Fenner's "two atmospheric stages" take in a liquid stage in the first place, and a solid stage in the second place, with modification of the solid objects by secondary fusion. It is considered most unlikely that "two atmospheric stages" such as postulated, could have been attained during the extremely short period

available for transit through the earth's atmosphere, considering the high speed of travel, for one of these postulated stages would require that the australites became completely molten throughout, otherwise the suggested trends in shape formation could not have arisen in the earth's atmosphere.

However, the ratios of width and depth measurements of many rounded australites (meaning "round in plan aspect") as graphed by Fenner (1938b, p. 200), show a relationship bearing out his earlier suggestions (1934, p. 65 and 1935a, p. 132) concerning progressive development from sphere- to lens-shaped forms (fig. 31).

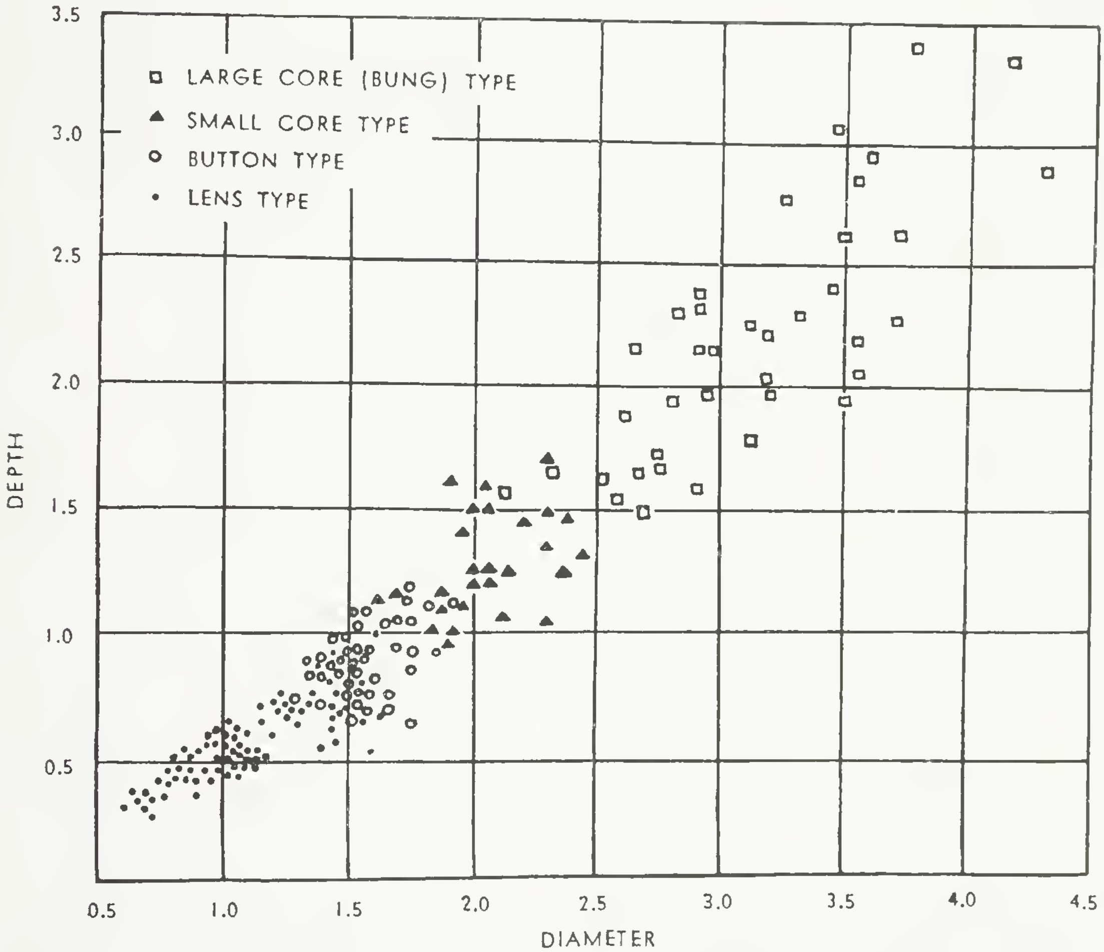

FIGURE 31.—Graph of depth-diameter relationships for lens-, button-, core- and bung-shaped australites (after Fenner, 1938).

Fenner found that in specimens weighing from one-third of a gram (lens-shaped forms) to 100 grams ("bung-shaped" forms), the width-depth ratios preserved a significant relationship to the forms. This suggests an evolutionary development from spheres, through "bungs", small cores and flanged buttons, to the extremely abundant final product, the lenses, which make up to 80 per cent. of large australite collections.

It has also been suggested that the development of secondary from primary forms of australites, results in primary parts remaining more stable (vertically shaded area in fig. 32), because it is thought that these parts cooled more rapidly (Fenner, 1935a, p. 132).

The original spheroid (broken circle in fig. 32) fused on its front surface, while spinning through the atmosphere, according to Fenner. At least half of the spheroid fused and flowed backwards. Portion remained adhering to the final form as a flange. The front surface and all the flange (stippled portions in fig. 32) are due to secondary fusion, the remainder representing consolidation from primary melting. There was thus considerable reduction of bulk and alteration in shape of primary forms, caused by frictional heat generated during rapid atmospheric flight and ablation. Primary shapes were thought to have formed almost instantaneously, the moment they came into existence as

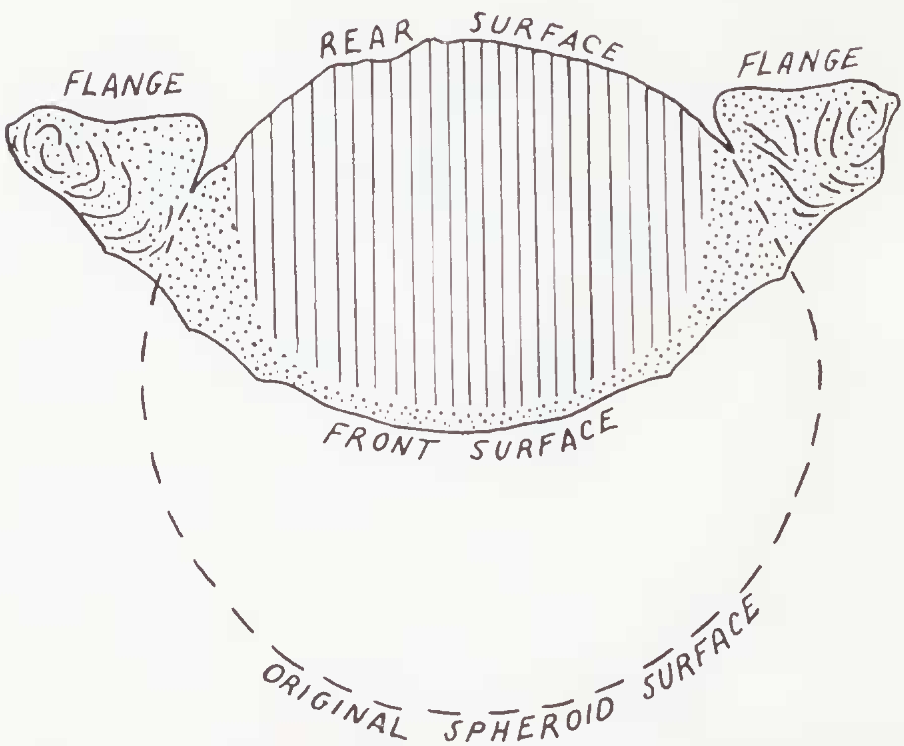

FIGURE 32.—Diagram showing development of a button-shaped australite from an original sphere. Primary portions shaded, secondary portions stippled (after Fenner, 1935).

discrete blobs of glass. The time taken for the development of secondary forms occupied but a few moments, just sufficient for melting, flowage and solidification of the glass, between the time of primary shape formation and the arrival of tektites on the earth. The amount of frictional heat requisite for secondary melting and flowage was small. Most of Fenner's suggestions here are acceptable, except that it is again inferred that the primary shapes formed in the atmosphere. In the writer's opinion, the primary shapes developed outside our atmosphere.

Further elaborating ideas of shape evolution as applied to the commonest and best known forms of australites, namely those that are round in plan aspect, Fenner (1938) started with the assumption that all "round" forms could be produced from original spheres (fig. 33).

Progressive backward flowage of glass melted from the front surfaces of postulated spinning blobs, accompanied by ablation, caused these original spheres to gradually pass into flanged, button-shaped australites of various sizes, and

from thence into the non-flanged group of the lenses. A stage was reached in the lenses when the glass mass was more stable than in any previous stage. Development beyond the stage reached by the smallest lenses resulted in forms being completely consumed during flight, in Fenner's view. In stages 2 and 3 (fig. 33), the dotted lines represent "bung" and "core" shaped australites, supposedly formed by cracking and flaking of less stable, originally hotter and rapidly cooled portions (Fenner, 1938).

In connexion with the origin of the australite "cores" (and "bungs"), the writer has suggested (Baker, 1940a, p. 493) that these forms can arise in at least three different ways, namely (*a*) from regular button-shaped australites by loss of flange on abrasion or from temperature variations after fall, followed by further equatorial flaking, (*b*) from the non-flanged lenses that suffered flaking of the rim regions in a similar way. Small, round cores 20 mm. and under in diameter, formed from the regular buttons, as shown by some cores

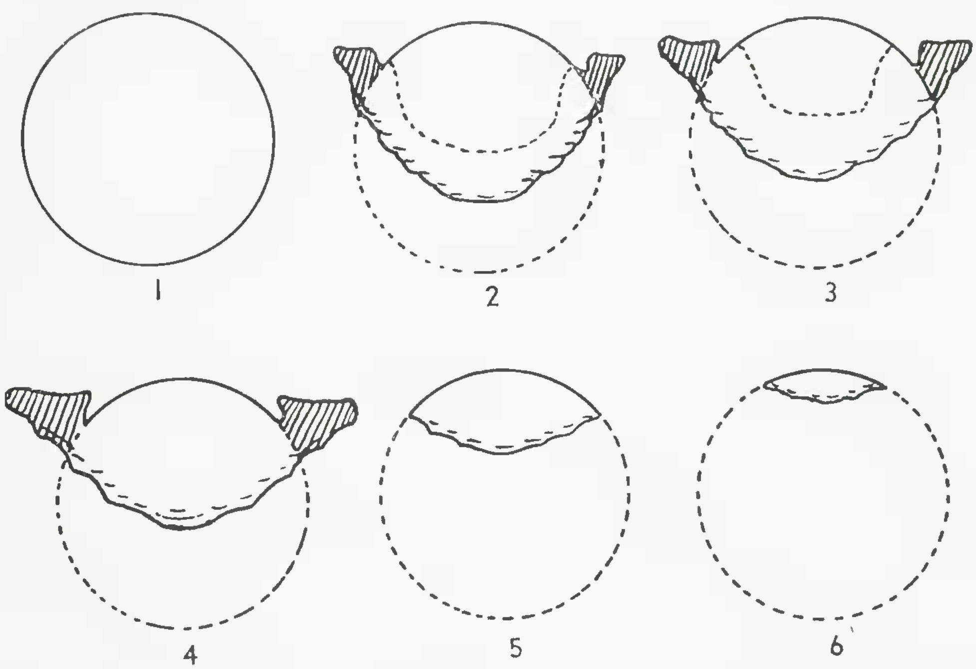

FIGURE 33.—Six stages in the development of button- and lens-shaped australites from original spheres (after Fenner, 1938).

having smooth bands averaging 2 mm. in width, marking the original positions of attachment of flanges, (*c*) by flaking away of unstable portions of equatorial regions exposed to greatest frictional drag, during atmospheric flight. Such a process is suggested in order to account for the beautifully marked, well-preserved equatorial zones of large round and elongated australite cores showing no signs whatsoever of weathering (cf. Plate X, fig. A).

Objections have been raised (Fenner, 1940) to the idea of formation of such australite cores by flight flaking, but the writer believes that this mode of origin is highly likely, in view of the fact that lenses are derived from flanged, button-shaped australites by flange shedding during atmospheric flight, as described by Fenner (1938)—an idea which in itself must entail loss of glass during traverse through the atmosphere.

The flaked equatorial zones on the larger of the australite cores, which are forms for which there is no evidence whatsoever that they possessed flanges at any stage of development, result from natural agents. They do not resemble secondarily chipped surfaces produced on australites by aboriginal man, and are not comparable with regions of flaking on smaller, conical australite cores produced by abrasion or by spalling on temperature changes on the earth's surface after fall. The flaking process is therefore attributed to a cutting action of the atmosphere due to frictional resistance during rapid earthward flight of these larger forms. The formation of flaked zones was partially assisted by gas bubble accumulation in outer parts of equatorial regions, as evidenced by the frequent association of bubble tracks and some bubble pits with these flaked equatorial zones (Baker, 1940a, p. 488). Their presence materially weakened equatorial zones, and rendered them more susceptible to fusion stripping and possibly some ablation. Remnants of areas of bubble accumulation are seen in Plate XV, fig IB, where numerous bubble tracks lead to a large bubble crater on the posterior surface. Admittedly there are some of the larger cores that evidently were not subjected to such a process, and such forms do not show a flaked equatorial zone (cf. Plate I, fig. N), or else only the merest vestiges of such a zone. Other examples are also known, such as the larger of the "indicators" described by Fenner, which point to some of the flaking having occurred as a result of the operation of sub-aerial agencies.

(b) Without a Spinning Motion.

Detailed studies of various aspects of australites have convinced the writer that australites need not have rotated during their atmospheric trajectory. Thus one finds that the fine flow lines on the anterior surfaces of australites—the surfaces that faced earthwards during flight—are more or less always of a radial character. If the australites were rapidly rotating, it would be expected that these flow lines would be spirally arranged. It might be argued that the so-called flow ridges on the anterior surfaces are sometimes clockwise spiral and sometimes anticlockwise spiral, and that rotation was therefore indicated. It should be remembered, however, that many of these ridges are concentric, and parallel the equatorial periphery of the australites. Moreover, it will be shown later that such ridges can arise as a direct consequence of the action of the atmosphere on the front surfaces of these fast-moving objects, without invoking that they rotated.

Then again, if australites rotated rapidly through the atmosphere, whether they were fluid throughout, or whether only superficially melted on the front surfaces, the writer can see no reason why flange glass should accumulate where it does—in the equatorial regions of the australites. Surely, during such rapid postulated rotatory flight, strong centrifugal forces would be responsible for throwing off such liquid matter completely. It is significant in this respect, that the width of the flange glass surrounding dumb-bell shaped forms (on the rare, complete forms still preserved), is more or less the same in the waist regions as around the bulbous ends. If dumb-bells therefore are to be pictured as rotating rapidly through the atmosphere like the propellers of an aeroplane, again any molten flange-building glass should have been centrifuged away.

Furthermore, if australites rotated, the internal flow patterns in the secondary flange structures would surely be concentric with the plan outline of the forms. Instead of that, thin sections of flanges reveal that they invariably possess the coiled character depicted in Plate X, fig. B, and Plate XI, fig. A. And this structure remains much the same, no matter where the section is taken

around the circumference of the form, and no matter whether the section is through a form such as a button, an oval, a boat, a dumb-bell, or a disc-shaped australite, in fact any flanged form. It is also significant that the drawn-out lechatelierite particles observed in thin sections, are elongated parallel with these coiled flow-line structures; they never seem to plunge obliquely into the glass, as might be expected if rotational forces had been superposed upon the backward migratory movement of flange-building molten or plastic glass.

The complexity of the flow-line patterns within the body portions of flanged australites, is scarcely that which would be expected, compared with the coiled character of the flange glass (cf. Plate X, fig. B), if the australites had been rotating as completely molten bodies within the earth's atmosphere.

It seems reasonable to assume, from the above evidence, that the characteristic structures of australites are such as do not necessitate rotation during atmospheric flight, but it will be shown later, that their primary forms, except those of the original spheres, were undoubtedly forms of revolution, but forms that were evidently produced in an extraterrestrial environment.

Before setting out the theory of origin invoking a non-rotary atmospheric flight phase for the development of the shapes of australites, it is necessary to examine evidence relating to certain physical characteristics of tektite glass.

It has been calculated that if only 1 per cent. of the energy which meteors possess on entering the earth's atmosphere at 40 miles a second, was converted into heat by air friction, and this heat was retained by the body, it would be sufficient to raise the substance of a tektite to melting point, and render it completely liquid (Grant, 1909, p. 447). On the other hand, it has been shown that the amount of heat generated by the passage of glass blobs through the atmosphere, considered in conjunction with heat of conductivity of the material, was insufficient to melt them to the extent some tektites were melted during the period prior to arrival on the earth (Watson, 1935; Opik, 1937; Spencer, 1937). Objections have been expressed to the ideas of Lacroix (1932) and Fenner (1934, p. 131) that as australites cooled, the combination of air resistance and some rotational motion of their own, formed lens, teardrop, or dumb-bell shapes, for several theoretical difficulties exist concerning such a shaping process (Watson, 1935). Basing his statements on the experimentally determined value of 0·002 cals./cm./°C. as the coefficient of thermal conductivity of Darwin Glass, Watson concluded that it would be impossible for sufficient heat from atmospheric friction to be transferred to the interior of tektites, to allow them to melt and take on the observed shapes. Darwin Glass is no longer accepted as a true tektite, but nevertheless, Watson's argument stands, for the coefficient of thermal conductivity of tektites is probably less than that of Darwin Glass. The only figure for tektites that the writer has been able to obtain, is one cited as being about that of artificial glass (0·0005), which is well below the value utilized by Watson in his conclusions. It has also been concluded that it is impossible for tektites to have been completely fused throughout their brief atmospheric flight, because iron and stony meteorites only show evidence of slight heating beyond a fused glassy crust a few millimetres thick (Spencer, 1937).

Based on the work of Opik (1937), the mechanics of meteor phenomena have been applied by G. F. Dodwell (Government Atronomer of South Australia) to australites (see Fenner, 1938b, p. 207) in the following way: Dodwell calculated that the thickness of a liquid film formed by friction in the earth's atmosphere would be only 0·001 cms. on a medium-size australite of 10 mm. radius. The temperature difference between the surface of the liquid film and the bottom of

the film would be enormous, according to these calculations, and the solid nucleus would remain cold inside. Thus it becomes apparent that for australites, only a thin surface sheet of the forward surface would be heated up at any given time during the phase of atmospheric flight earthwards, to a temperature sufficiently high to result in plasticity, and there is no need to believe that at any time did they become completely molten in the atmosphere. The temperature of the front surface need only be raised to something over 900° C. for softening of tektite glass to occur, as already shown by numerous heat treatment experiments with tektites from the various groups. Ablation, which involves liquefaction and immediate removal of material from the heated surface sheet, certainly seems to have occurred during the late stages of australite shape development. This would require rather higher temperatures, something over the temperature of 1,324° C. at which australite glass passes over completely into the liquid form. Some of the glass was most probably volatilized, but the temperature of volatilization of australite glass has not been determined; all that is known from this aspect, is that carbon arc fusion experiments reveal that in the region of 3,000° C., the temperature of the electric arc, australite glass volatilized. Most of the heat generated by frictional resistance of the earth's atmosphere, would no doubt be used up in the process of front surface film liquefaction of australite glass, and hence no reason exists for pre-supposing that australites became completely molten during atmospheric flight, particularly when the low coefficient of thermal conductivity is also taken into account.

Of particular importance in the development of any theory of the formation of the shapes of tektites, are the results of the studies of iron and stony meteorites as elaborated by Lindemann (1926). The recorded velocities of meteorites are given as 10 Km./sec. to 100 Km./sec., and Lindemann stated that meteorites disappear from the vision at any height above ground level. A cap of compressed gas that forms in the front of an advancing meteorite, protects it from loss of heat. Heat flows from this cap of gas and ultimately causes particles of the meteorite to volatilize. A meteorite appears to the vision when evaporation is appreciable, and this only occurs after the cap of gas has been formed, i.e., when the chance of molecules escaping laterally from the meteorite without further collision with an air molecule is small. The total heat developed is equal to the amount of air accelerated in unit time, and this is the product of the atmospheric density, the cross section and velocity of the meteorite, multiplied by half the square of the velocity. From this relationship, the flow of energy available for heating and volatilizing in terms of the atmospheric density, can be determined. The temperature in the cap of compressed hot gas in front of the meteor, must attain a temperature at which iron or olivine will evaporate, if the meteor is to appear to the vision. The compression ratio is: $\frac{3v^2}{2V_0^2}$, where v = the velocity of the meteorite, and V_0 is the molecular velocity. The maximum temperature at the surface of the meteorite in terms of its velocity and of the initial temperature of the air, is 2,000°C., if olivine and iron, which evaporate slowly, become visible. Lindemann believed that the temperature of compressed air could only reach 2,000°C. if the initial air temperature was 300°C., and that above 60 Km., the effect of CO_2, water, &c., would be outweighed by the effect of ozone, so that at this height, the air should approach the equilibrium temperature for ozone, viz., 300°C. Recent researches into the layers of the atmosphere have shown relatively wide variations in temperature from layer to layer, but considering the fact that tektites would take but a few seconds to traverse the atmosphere, it is believed that temperature differences from layer to layer, would have very little effect on the generation of the shapes of such tektites as the australites.

A temperature of 1,400°C. is more than ample to soften and completely melt any of the known tektite glasses, under conditions operating at the earth's surface, as evidenced from the heat treatment experiments of Lacroix, Linck and others (see Chapter III). In terms of Lindemann's reasonings, the maximum surface temperature of visible meteorites is 2,000°C., but it is not important to know, and therefore not argued herein, whether tektites would also have become visible during their earthward flight through the atmosphere. Temperatures much over 2,000°C. are therefore not necessary, in tektite considerations, but it has become evident from studies of the australites in particular, that these objects were subjected to a certain degree of secondary melting during their atmospheric trajectory. Even though certain physicists have disbelieved in the past that tektites could have become hot enough to melt by friction during their transit through the earth's atmosphere, Lindemann's calculations for iron meteorites could readily be applied to glass objects like the tektites. Under such circumstances, it seems reasonable to assume that tektites entered the earth's atmosphere from outer space in an originally cold state, and at sufficiently high speeds, could have been melted on their forward surfaces, where sufficiently high temperatures were generated. Whether they became molten throughout is extremely doubtful, because the rate of heat transference in natural glass has been shown to be very low. It is not required, however, that tektites should have melted right through during the phase of atmospheric flight, and if they did, at their high velocities they should then have become entirely dissipated. All that is requisite to adequately explain their secondary structures, e.g., such as those on the anterior surfaces of australites in particular, is that at supersonic speeds, superficial sheet fusion occurred over a limited period of time, sufficiently long to allow for secondary features to form and be preserved.

With the immediately foregoing observations and evidence in mind, supported by a long background of gradually evolving theories of origin of tektites, the writer ventures to present the following hypothesis as an up-to-date and possibly rational explanation of how the shapes of certain tektites, more especially the australites, have been developed under the terms of gas dynamics at ultra-supersonic velocities. The writer does not lay claim to a thorough knowledge and understanding of aerodynamics under the conditions of ultra-supersonic flight through the earth's atmosphere, more particularly as this branch of engineering science is still in its infancy. The theory is presented therefore, with an essentially geological background, as a working hypothesis that seems to adequately explain many secondary features of the modified forms that the australites possess, and which may ultimately have some considerable bearing on future ideas concerning man's efforts to attain even greater supersonic speeds than have been realized to date.

AERODYNAMICAL CONTROL OF AUSTRALITE SHAPE DEVELOPMENT UNDER CONDITIONS OF ULTRA-SUPERSONIC FLIGHT.

As an introduction to this hypothesis, it is necessary to select some starting point, and since a great weight of evidence points to tektites having been cold and solid when they first encountered the earth's atmosphere, it is presumed that the australite varieties of the tektite family, were already pre-formed and possessed certain primary shapes of limited number and simple type. Secondary fusion, caused by the heat generated by atmospheric friction, resulted in the modification of the original shapes of australites. It has been indicated earlier that the initial forms were those of spheres and of the common figures of

revolution, as evidenced from detailed studies of the arcs of curvature of the surfaces of australites, and from the relationships of the radii and arcs of curvature to the size dimensions of the ultimate secondary forms that australites possess (Baker, 1955a, 1956).

In this connexion, Jeans' (1919) theories relating to stellar dynamics are most instructive, and lend support to the suggested development trends in australites. A non-rotating mass would generally assume a spherical shape under the action of its own gravitational forces. The best known configurations of equilibrium in rotating, homogeneous masses, are ellipsoidal. These are tide-generating masses in which dynamical motion supervenes, so that on reaching a certain elongation, ellipsoidal bodies develop a series of furrows or constrictions. Jeans considered that the longest spheroid of molten material that was dynamically stable, would pass into a pear-shaped body with the development of a constriction. This is unstable in rotation, and so further elongation and constricting of such a body, by several harmonic displacements, resulted in the passage through dumb-bell-shaped bodies, until subsequent configurations became separated, smaller bodies of various shapes and sizes.

Extending these general principles to the development of the infinitely smaller bodies that we know as tektites, an extraterrestrial birthplace is envisaged, where molten material was dispersed as molten drops, the majority of which did not rotate, cooled rapidly, and hence remained as spheres. A small proportion, approximately 20 to 30 per cent. where the australites are concerned, were disrupted as molten rotating bodies. Some rotated at slow speeds of revolution, but cooled relatively rapidly to produce oblate spheroids. Others rotated more rapidly about an axis, and became elongated into prolate spheroids possessing varying, but nevertheless limited, ratios of length to breadth. The few that rotated even more rapidly, developed constrictions and passed into the shapes typical of dumb-bells of revolution. An even smaller number continued to revolve and constrict until parting occurred in the waist regions, thus producing two apioids of revolution. Geometrical forms such as the paraboloid and annular torus were evidently not developed. Having been thus formed, by rapid melting and ejection from some extraterrestrial body of essentially acidic composition, and relatively rapidly cooled, the spheres cooling slightly more quickly than the elongated primary forms, a cloud of these glassy, relatively homogeneous objects ultimately commenced their period of wandering in space, a wandering that was to continue for some 31½ million years at least for the australites.

Stair (1954, p. 221) contends that tektites have melting temperatures and general physical characteristics (striae, strain and inhomogeneity), which call for a forming temperature between about 1,500 and 2,500°C. Glasses of this type are regarded as not being producible as flash products resulting from a collision or short-period heating by any other means. Long periods of time are considered requisite for the different oxides composing the glass to properly fuse and mix into a more or less homogeneous glass product. During this time, the temperature must be well above the melting point of the glass. Stair therefore pictures the incomplete mixing shown by the streaky character of all tektite glasses as being expected under conditions where new materials are being constantly added to the glass batch. Nevertheless, despite this reasoning, the development of the primary shapes of such tektites as the australites, calls for rapid fusion and rapid chilling, spheres for example, must be produced more or less instantaneously. Furthermore conditions may well have existed in the extraterrestrial birthplace of tektites for rapid fusion followed by rapid cooling, without the need for long periods of time and the constant addition of new materials to the forming glass.

The surfaces of these small bodies of glass were not entirely smooth on rapid chilling of the primary shapes. The escape of gas bubbles, which must have occurred very rapidly, created minutely pitted surfaces, but in places where gas pores were less abundant, primary flow streaks and " swirls " were generated. In addition, complex, in places highly contorted internal flow patterns, were pre-determined, with which were associated the incompletely resorbed lechatelierite particles.

In possession of these shapes and initial structures, there came a time in the recent epoch of the earth's geological history, when the cloud of australites was drawn into the earth's sphere of attraction. Such a cloud must have been of limited size, to account for the limited distribution of this type of tektites upon the earth's surface. As a cloud, probably of not particularly great density, it is likely that the shape was elongated, with somewhat denser forms at the head, and less dense forms at the rear. Investigations of specific gravity values reveal that material of similar density occurred among all the primary shapes of the australites in the cloud, thus explaining why the present distribution of australites, with the marked chemical gradient across the Australian continent, reveals similar proportions of the various shape types among higher density forms as among lower density forms.

The question now arises as to the effect that rapid speeds of transit through the earth's atmosphere, had upon the forward surfaces of these pre-determined shapes, shapes that were largely spheres of varying but very limited and small sizes, with a smaller proportion of ellipsoidal shapes, fewer dumb-bell and apioid shapes, and even more rare aberrant shapes that had evidently become distorted by accidental collapse, collision or such phenomena in their extraterrestrial birthplace.

By analogy with meteorites, the speed of transit of the australites through the earth's atmosphere could have been initially some 180,000 miles per hour at the onset. But this speed was soon considerably reduced. At approximately 70 to 80 miles above the earth's surface, the cloud of australites was slowed down, and they fell to earth along a parabolic path. At this height, the rate of fall would be in the region of 21,600 miles per hour. The australites would thus traverse the remaining distance to the earth's surface in a matter of a few seconds. During this period, the primary shapes were subjected to considerable modification. The motion involved was that of rapid forward propagation only, with no rotation whatsoever, although a few forms provide evidence of having wobbled slightly, apparently as a consequence of the development of a small degree of buffeting at high speeds. A few miles above the earth's surface, the australites lost speed rapidly, more so in the denser, lower layers of the atmosphere, so that they were enabled to land without being smashed to pieces on contacting hard ground, and without becoming too deeply buried on striking soft earth. Moreover, at this stage, the front surface no longer possessed a thin fused film and the australites had at no time during atmospheric flight become completely fluid or plastic, hence there could be no flattening of any of the forms on impact.

Thus the zone of formation of the secondary modifications of the primary shapes of australites existed between certain limits above the earth's surface, probably not more than approximately 70 or 80 miles up in the first place, and five or thereabouts at the most in the end phases. It is apparent that during this formative phase of the secondary shapes, the nature of the airflow over and past the forward surface of each australite must have changed markedly and continuously as their speeds decreased, but was no doubt maintained as a steady flow while ultra-supersonic speeds obtained.

In experiments relating to fluidal flow past bodies, fluids are made to flow at varying speeds around the bodies, because it has so far proved more practicable to note the effects of flow in moving fluid, the velocity of which can be controlled. Flow-streaming produced around a stationary cylindrical object, sometimes shows boundary layer disturbance in the turbulent region as a pattern (cf. fig. 34) closely resembling back portions of flanged australites, suggesting some control of the shapes of australites in their equatorial portions, by motions in the boundary layers of the fluid (air) through which they rapidly moved.

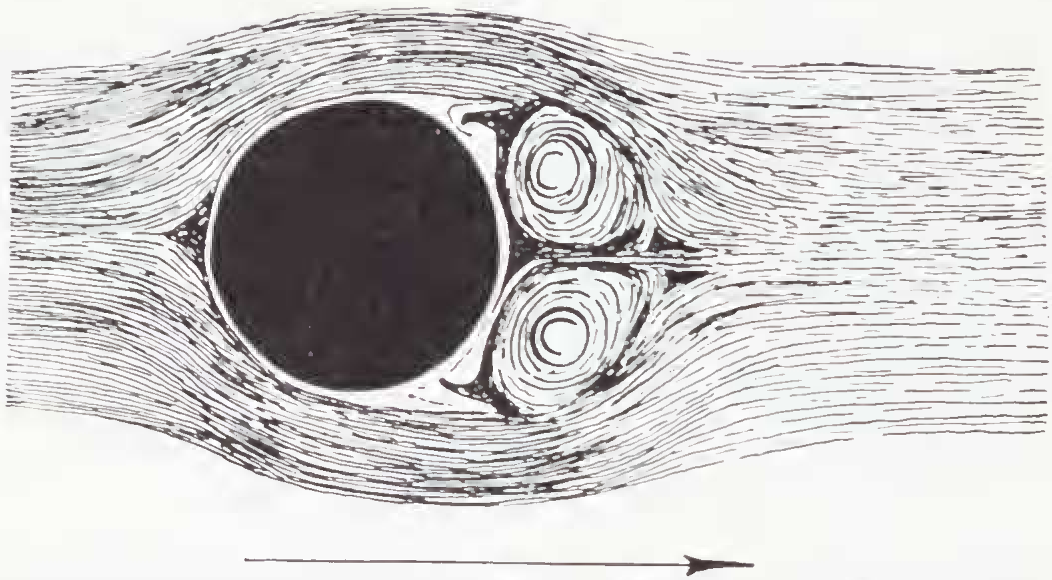

FIGURE 34. Fluidal flow past a cylindrical body. (Stream velocity small.) Showing boundary layer and reverse flow with secondary vortices. Pattern in boundary layer flow at rear of cylindrical body resembles somewhat the posterior surface outline of certain button-shaped australites (after W. F. Durand "Aerodynamical Theory, vol. III," 1935).

Since australites are small bodies that evidently travelled at ultra-supersonic speeds through the atmosphere, great stream velocities would be generated, and boundary layers in the fluid medium (air) would of necessity be thin layers. Within these thin layers, all frictional effects between objects and fluid take place. Density variations of the air throughout the formative zone of secondary shape development cannot be accurately gauged, but probably only had minor effects on the ultimate character of the forward surfaces of tektites. Any density variations in the tektite glass itself can probably be neglected, since they would be insignificant in what now is, and undoubtedly was throughout atmospheric flight, a relatively, although not entirely, homogeneous* glass. The coefficient of thermal conductivity of australite glass being low, approximately that of artificial glass (0·0005), the rate of heat transference from front to back surface would be of little or no account. Of special importance is the fact that it seems as though australites traversed the atmosphere so rapidly that insufficient time was available for frictional heat to raise the interior and the rear surface of each australite to a point when it would become completely molten (1,324° C. for australite glass). It is therefore believed that front surfaces of australites were subjected to partial,

* Homogeneous in not having a crystal fraction—the glass itself reveals slight inhomogeneities in possessing "schlieren" from limited liquid immiscibility.

superficial (0·01 mm. thick) "front-skin-melting" under the influence of frictional heat, while rear surfaces remained cold, especially as regions of "dead air" must develop immediately behind the fast-moving objects.

As to frictional and pressure effects on australites, it is known that no frictional forces operate at the poles of a sphere falling through a viscous fluid, because the velocity components and the pressure involve both the radius of the sphere and the velocity at infinity. Pressure is greatest at the front pole, least at the rear. Frictional forces are greatest at the periphery (equatorial regions), but also operate to some degree on the front surface from near the front pole outwards. Effects of the frictional forces would vary slightly with the radius of curvature of the forward surfaces, and would partially depend upon certain significant and specific limiting values of the original (50 mm.) as compared with the final (5 to 25 mm.) diameters of the objects. Such a combination of factors would probably result in an optimum position of heat stability; the degree of viscosity attained by the heated portions of any particular front surface was controlled by the temperature developed from frictional resistance of the atmosphere during flight, and hence by the velocities of the australites.

Australites entered our atmosphere at ultra-supersonic velocities, therefore certain special aerodynamical factors became operative. Theories of aerodynamics have so far been concerned principally with the streaming of fluids past objects, but with the australites, effects of the external streaming of fluids on the fast-moving objects concerns us most. The application of known and accepted aerodynamical theories to the study of australites, provides a basis for speculation about factors causing the generation of secondary modifications of primary shapes, and concerning the production of certain external features on their forward surfaces.

At the outset, with the high Mach Number* that australites would possess, there would come into play aerodynamical factors operating upon the forwardly directed surfaces of the initial primary forms in such a way as to produce the modified shapes now possessed by australites.

In the first place, at ultra-supersonic speeds, a state of steady flow or disturbance of a permanent type was set up in shock waves produced in the fluid medium (air) ahead of each australite body. The shock waves† are regarded as sheets where there is a discontinuity of velocity, i.e., places where rate of change in velocity and density of the fluid become infinite. They travel in front of a fast-moving body producing them, at the same speed and in the same direction as that body. At all other points, for example along the sides of the objects, shock waves move obliquely to the direction of flight, as indicated earlier by a bullet in flight, shown in sketch form in fig. 35.

Each australite can now be pictured as travelling earthwards through the atmosphere at ultra-supersonic speeds, without rotation. Commencing with a primary sphere of homogeneous glass, a frontal shock wave would be formed

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* The Mach Number (M) is the ratio of the speed of supersonic flow to the speed of sound, so that if $M = 1 \cdot 0$, the speed of supersonic flow equals the speed of sound, which is 760 m.p.h. at the standard sea level temperature of 15° C. Australites are estimated to have had a Mach Number of approximately 20 to 25 at a height of some 70 to 80 miles above the earth's surface.

† Cf. W. F. Durand, "Aerodynamical Theory, Vol. III."—Julius Springer, Berlin, 1935.

in the air piled up ahead of such a fast-moving object. The arc of curvature of the shock wave would be a little greater than the arc of curvature of the sphere. The air is brought to rest in the shock wave, which is a narrow zone of intense compression where greatly increased temperatures arise. Any air that flows over the front surface of the primary sphere can do so only after penetrating the narrow arcuate region of the frontal shock wave. Between the shock wave and the front surface of the sphere the air expands but high

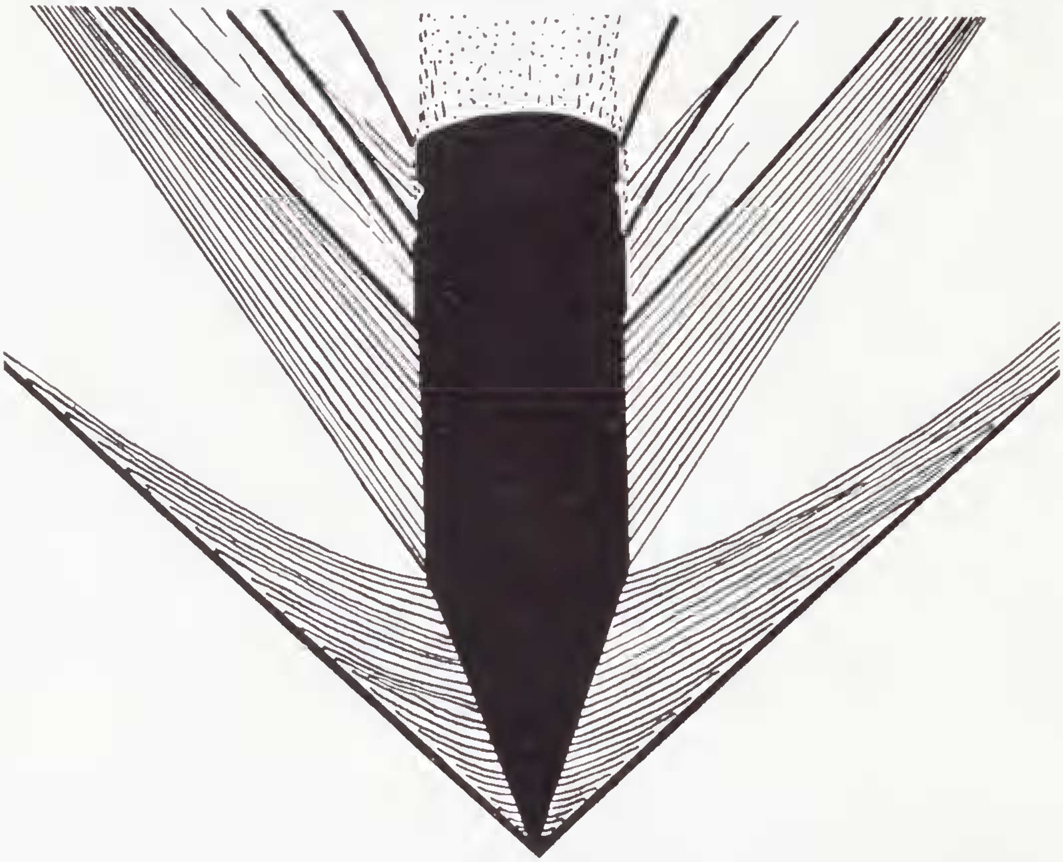

FIGURE 35.—Sketch from photograph of a bullet in flight. Showing shock wave and shock wavelets along the head and parallel sides of the conical-headed projectile. Speed supersonic (1·576 times greater than that of sound). Region of "dead-air" at rear of projectile; shock wavelets arise from surface irregularities along the parallel sides (after W. F. Durand—"Aerodynamical Theory, vol. III," 1935).

pressures, and consequently high temperatures persist. All the mechanical energy produced at these ultra-supersonic speeds, would be converted into heat, due to the viscosity and conductivity of the air in the zone behind the frontal shock wave. Consequently, as long as these high speeds prevail, a cap of highly heated compressed air travels ahead of the australite, as diagrammatically illustrated in figure 36.

During the early stages initiating processes that were ultimately responsible for developing the secondary shapes of australites, this cap of hot, highly compressed air supplied the temperature rise necessary to the softening of thin films of the tektite glass in the front polar regions, where pressures would be at their greatest. Consequently, glass in the front polar regions was fused

and removed, partially by fusion stripping, and partially by ablation. As this process progressed, the arc of curvature of the front surface of the sphere became less steep as its radius of curvature increased. In the early stages, it has been conjectured that an equatorial skirt of secondary shock waves would be present around the equator of the sphere (cf. Baker, 1956), but these would

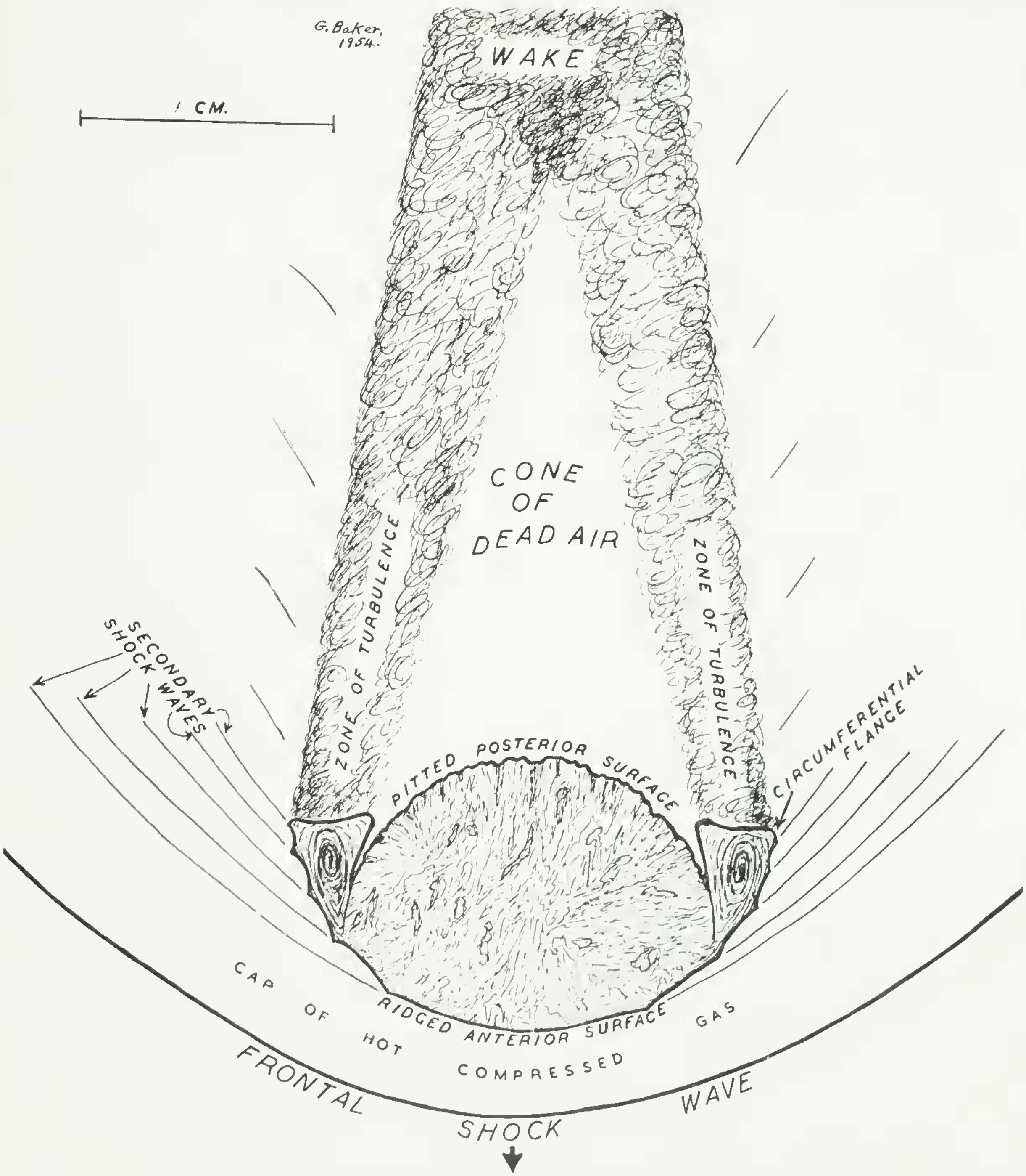

FIGURE 36.—Sketch diagram illustrating the phenomena conjectured to be attendant upon the final stages of supersonic flight through the earth's atmosphere of a button-shaped australite, after having been modified from an original sphere of glass that initially travelled at ultra-supersonic velocities.

play little, if any, important part in shape formation at this stage. In them, compression, although high, would not be expected to be as intense as in the frontal shock wave, and they would lie very obliquely backwards and be somewhat detached from the sphere, because of thickening of the boundary layer of air in these regions as induced by the objects having such high Mach Numbers.

While the process of frontal-thin-film-melting is proceeding, turbulence is created behind the fast-moving sphere where the main air flow becomes separated in the equatorial regions. This arises from the action of reverse and secondary reverse laminar flow producing vorticity in the relatively thin boundary layers of the atmosphere in contact with the surface of the sphere. Within the thin boundary layers, all frictional effects arise between the anterior surface of the australite and the medium through which it has its trajectory. Stresses therefore arise in the air along the anterior surface, producing skin friction as a tangential component, and stresses also arise in the positions where turbulent flow is generated in equatorial regions, producing form drag. Immediately behind the posterior surface of the sphere, a cone of virtually dead air would be present, thus ensuring that the posterior surface was maintained at temperatures well below the fusion temperature of australite glass.

Continuation of the process of fusion stripping by skin friction aided by ablation, reduced the front surface of the sphere to various extents, as evidenced from studies of curvature size relationships of the ultimate secondary shapes (cf. Baker, 1955a, 1956). At some stage, however, and evidently a relatively early one, the flaked equatorial zones on some of the larger core-like australites, were produced by a process of intense equatorial fusion stripping. This would come about as an effect of the separation of the main air flow stream in equatorial regions, where in such a region, occurs the transition zone in which laminar flow in the thin boundary layer ends, and turbulence supervenes. The turbulence thus emerges from the thin boundary layer, and being packed with vortices, would generate much more intensive friction, and hence initiate a period of more intense fusion stripping in equatorial regions.

Other, smaller spheres, were reduced in bulk by approximately 60 to 65 per cent. by fusion stripping and ablation, so that the front pole of the modified sphere had now passed beyond the original centre of the primary sphere; the arc of curvature of the front surface had become a little flatter, and the equatorial edge of the form had gradually receded beyond the equatorial zone of the original sphere. A situation has now been reached where all the glass fused from the front surface need not be whipped away by skin friction, some became caught up in eddy currents associated with the turbulent zone leaving equatorial regions, and coiled up on the equatorial edge of the posterior surface, as indicated in figure 36.

Near the final stages of flight, as the velocity of the australite considerably decreased, and a region was reached where ordinary supersonic speeds prevailed, just prior to passing from transonic into subsonic regions, front surface fusion was brought to an end, and small amounts of drag at that stage resulted in whipping away of very thin films of somewhat soft glass to produce the so-called "flow troughs" separated by ridges. This is evident from thin sections which reveal that the "flow trough" structures cut into the secondary internal flow line patterns immediately below the surface (see Plate XII). At this stage, the aerodynamical flow phenomena were thus much less potent in their shaping

and sculpturing effects. The situation has been reached where the equatorial skirt of subsidiary shock waves has vanished, and less oblique subsidiary shock waves arise from the small projections provided by the ridges. Since there are small zones of expansion behind each of these subsidiary shock waves, it is possible that the trough-like structures were partially scoured-out during the limited period of existence of such subsidiary shock waves.

The operation and effects of aerodynamical flow phenomena at ultra-supersonic, followed by the effects at supersonic and transonic speeds outlined above for a sphere of tektite glass, would apply equally as readily to the other primary shapes of australites such as the ellipsoidal primary forms, although the situation might be rather more complicated by the dumb-bell-shaped forms with their " bi-polar " surfaces.

For all the australite shapes therefore, shock waves were produced at high speeds of flight, and only in shock waves can a state of steady flow of a permanent type be set up, when the motion of the objects is limited to one direction. Under such circumstances therefore, it is difficult to imagine any rotation of these objects during the phase of atmospheric flight. There seems to be little doubt that the concentric ridges on the front surfaces of australites can be explained in terms of the action of aerodynamical flow at high velocities, while the clockwise and anticlockwise spiral ridges on some specimens have been explained (Baker, 1956) in terms of control, under identical conditions, by the appearance at different levels to which ablation and fusion stripping had proceeded, of small etch pits from which the ridges have been noted to spiral outwards. Alternatively, such spiral ridges may have been induced to some extent by the generation of a slight wobble produced on some specimens as an outcome of form-drag. Then again, it is not surprising that concentric ridges usually become wrinkled towards the equatorial peripheries of the secondarily produced shapes, for these are situated in regions where complexities arise as a result of the stresses generated at the onset of turbulent flow in the separating boundary layers of the air.

There may appear certain flaws in the above postulated Aerodynamical Control Theory of australite shape development, but the theory does seem capable of explaining most, if not all, of the characteristic secondary shapes attained by australites and also the special features that their forward surfaces possess. The theory may not be as easily applied to other types of tektites, none of which possess the distinctive anterior surfaces, flanges and concentric, &c., ridges that are found on australites. Variations between the shapes of different members of the tektite family, have been explained in the past in terms of different types possessing different viscosities. Such an explanation no longer holds if all tektites entered the atmosphere as cold bodies, with already preformed shapes. Shape differences would thus have to be explained more in terms of either their age differences, under which circumstance the older forms would have to be considered to have lost, by weathering, certain features produced under the operation of aerodynamical flow phenomena at ultra-supersonic velocities, or else in terms of differences in speed of atmospheric flight and differences of distance travelled through the earth's atmosphere. There is no doubt that the australites are the youngest of the tektites, and hence among the least modified by tertiary processes such as the action of terrestrial agents of erosion; on the other hand they may also have passed through the atmosphere at much greater speeds than other varieties of the tektites, hence their unmatched secondarily modified shapes and forward surface structures.

The formation of round disc, oval plate and bowl-shaped australites is difficult of explanation under the terms of any of the theories of shape development so far propounded. They can be more readily envisaged as resulting from special circumstances of aerodynamical control, commencing with very small original primary forms. Thus the round discs derive from the smaller spheres, and oval plates from the smallest spheroids of which we have evidence. Discs are an advanced stage of flattening of the smallest known button-shaped australites. These small buttons, known more especially from the Port Campbell district of south-western Victoria, have been reduced during atmospheric flight to a thickness of from 2·0 to 4·0 mm., and their radii of curvature of the posterior surfaces range from 2·0 to 5·0 mm. This indicates that original primary spheres of from only 4·0 to 10·0 mm. in diameter have been reduced by ablation and fusion stripping by the operation of the aerodynamical phenomena described above for larger buttons, &c., at ultra-supersonic velocities. Under such circumstances, their anterior surfaces became much flatter compared to that of the posterior surfaces, the radii of curvature of the anterior surfaces now being 15·5 to 28·0 mm. Such small forms are flanged, and usually the flanges are somewhat flattened and at times of greater bulk than the small remnant core or body portion. It is only a step further for such small buttons to pass to the disc-like australites (Plate V, fig. E), which are only 1·0 to 1·5 mm. thick, and which have a minute core surrounded by a broad (in comparison), thin, flat flange which possesses the coiled internal character of flanges developed on larger and smaller buttons. In other words, these discs have now become virtually no more, no less, than flanges essentially (see Baker, 1944, Plate I, figs. 8 and 10). Some of the small original spheres, and any even smaller ones that may have existed, have no doubt been completely dissipated by ablation and fusion stripping during ultra-supersonic flight. This would explain why microscopic australites do not seem to exist, although they have been carefully searched for in the Port Campbell australite centre of concentration. It is scarcely likely that microscopic australites having complete, secondary modified forms, will ever be found, for all forms below a specifically limited lower size have evidently been completely ablated and dissipated, for the reason that ablation depends essentially upon the size of the surface, and with diminishing volume, the relative size of the surface increases. In a somewhat similar, but not quite identical way, raindrops that reach the earth, have a certain minimum size.

Regarding the discs, which are essentially flat or sometimes have anterior surfaces of infinite radius of curvature, as therefore coming from small spheres, it is evident that rotation about their polar axes would only unnecessarily complicate the aerodynamical phenomena propounded herein for their development, and for reasons already set out, rotation during the atmospheric phase of flight is eliminated as a motion responsible for shape development. As the small, original spheres became flatter and smaller by ablation, it is evident that the nature of the airflow at ultra-supersonic speeds must have changed considerably, so that rather more special aerodynamical conditions are present for them, compared with those already outlined for larger australites. The major difference would be in the nature of the frontal shock wave, for whereas the shock wave ahead of the larger forms lies obliquely down the airstream, because of the arcuate character of the forward surfaces of these larger forms, the shock wave ahead of the small, flatter australites, would be normal to the airstream, i.e., parallel but ahead of their anterior surfaces and thus at right angles to the direction of propagation of the objects. The shock waves have thus passed from being originally arcuate and parallel with the front surface of the original small sphere, to straight and parallel with the flattened surface of

the front of the secondary form. However, during the all important formative stages of the secondary shapes as we now know them, the frontal shock wave was fundamentally of the oblique type, in which pressures, which depend upon deflection, are seldom more than 50 per cent. of the pressures generated when perpendicular shock waves are formed ahead of a perpendicular reflecting surface. Near the final stages of atmospheric flight, when the effects of supersonic flight were diminishing, and the transonic region was near at hand, these thinned, ablated, small forms evidently became flattened, for then their frontal shock waves would be perpendicular, and thus the pressures would be up to 50 per cent. greater than hitherto; this would immediately lead to greatly increased drag on the anterior surface, and being such thin forms (1·0 to 1·5 mm. thick), some were evidently just softened enough to cause either collapse of the form, or else bending backwards into the bowl-shaped forms. These bowl-shaped forms (see fig. 18) have small (5 or 6 mm.) front surface radii of curvature, so that oblique frontal shock waves would be re-established, and pressures reduced again for the very final stages of supersonic flight. At this stage, both the anterior and the posterior surfaces of the objects are now directed in the same sense, i.e., the forms are bowl-shaped, and the degree of backward bending of plastic glass has determined the depth of the bowls, which varies from 1·0 to 3 or 4 mm., although the thickness of the glass remains 1·0 to 1·5 mm. Having passed from the end of the supersonic, through the transonic and into the subsonic region, these thin disc-, plate-, and bowl-shaped australites of small size, are no longer heated at any point whatsoever, and it is conceivable that as cold bodies, they would reach the earth's surface by a process of wafting down, rather than by following a more direct line of flight, for they are so thin and light in weight, that a mere sharp puff of air will remove them from a bench-top on to the floor several feet away. Thus, such fragile forms, if wafted down, would not necessarily become broken upon contacting the earth's surface, but some have since been fractured and fragmented by a tertiary process—that of weathering while they lay upon the surface of the earth. The hypothesis outlined above would explain the origin of the small, flattened types of australites without recourse to the old idea of impact with a hard surface causing flattening of plastic material, and it is believed that all forms of australites were completely solid and cold on impact.

ORIGIN OF HOLLOW TEKTITES UNDER THE TERMS OF AERODYNAMICAL CONTROL.

As early as 1898, Walcott had recognized that the presence of a large internal bubble in a hollow australite from Horsham in western Victoria had no influence whatsoever upon the external configuration of the object. This is borne out by recent studies of hollow australites. It becomes obvious that the preservation of hollow forms as complete entities throughout the operative phases of fusion stripping and ablation at ultra-supersonic velocities, demands the original development of a primary hollow form (most were spheres, but some were spheroids) possessing an eccentrically disposed internal bubble, so arranged within that the walls of tektite glass were thicker at one pole than at the other. In company with the other shape groups of the australites, it is therefore necessary to conclude that hollow forms were primary, and that they were generated as such in an extra-terrestrial environment. It is a matter for speculation how such hollow forms were generated in the first place, but there seems little doubt that they were subjected to similar frontal ablation as other forms of australites (Baker, 1956). A hollow form with an eccentrically placed internal bubble would be expected to travel along its line of trajectory through

the earth's atmosphere, with the thickest wall forward (see fig. 21), so that the forwardly directed surface had thicker walls than the posterior surface. All hollow australites, of which there are comparatively few known as complete forms, provide evidence which indicates that this expected position was actually a stable position of forward propagation. Those with sufficiently thick anterior surfaces, withstood fusion stripping and ablation to the same extent as the solid round cores of similar outline, and upon these anterior surfaces, similar sculpture was generated. Some forms, however, were subjected to excessive ablation compared to the thickness of the walls of their forwardly directed surfaces, consequently the internal bubble was " melted into ", as evidenced by certain specimens that have inrolled edges to what remains of the anterior surface of the original hollow form. These inrolled edges show evidence of secondary flow of glass over the collapsed edges and a short distance inwards towards the inner walls of the original internal cavity with its typical " hot polish ".

It is thus seen that the secondarily modified shapes of original hollow forms, have been generated in much the same way, by the operation of similar aerodynamical phenomena, as outlined above for australites that were solid. It is of interest to note in this connexion, that " surface scales " from spheres of rizalites found at Pugad-Babuy in the Philippine Islands, show one end curled-up. This has been regarded as indicating deformation after shattering of the original spheres, which were supposed to have " exploded " in the air while soft (Beyer, 1934).

As concerns the initial formation of hollow tektites, it has been expressed that a hollow australite from Kangarco Island, South Australia (see Plate XIV, fig. 1) could not be admitted as having a form that resulted from being blown up with air while in the atmosphere, and since the art and technical achievements of pre-historic tribes were regarded as being considerable, confidence was placed in the thought that such a hollow form could be ascribed to the work of human beings (Berwerth, 1917). Then the hollow forms of billitonites were thought to have been produced by a rapid pre-atmospheric chilling of the outside of the glass, thereby causing gas to leak to the interior of the balls; during transit through the atmosphere, outer portions were thought to have been re-softened, so that a negative pressure would prevail in the gas inside the tektite (Linck, 1926). Linck's idea is thus based on an extraterrestrial origin of hollow tektites, and if the Aerodynamical Control theory of secondary shape modification of australites is fundamentally correct, hollow australites must have been formed outside the earth sphere. Whatever the controlling influence in their generation as hollow bubbles of glass, it is evident they were formed in an environment free of oxygen, free of nitrogen, and free of the gases associated with terrestrial volcanicity.

EXPLANATION OF CERTAIN OTHER FEATURES OF TEKTITES IN TERMS OF THE AERODYNAMICAL CONTROL THEORY.

In support of the theory herein elaborated, that aerodynamical control was fundamentally responsible for the production of the secondary shapes possessed by australites, the following features are discussed in the light of the various phenomena attendant upon high speeds of flight through the earth's atmosphere.

In the first place, it is more rational to expect glass fused from front polar regions of anterior surfaces, to migrate to equatorial regions, there to be built up into flange structures at a stage when favourable conditions existed for such accumulation, than to consider the flange glass as resulting from flowing down the inside walls of a glass pellicle as demanded by the terrestrial volcanic Bubble

Hypothesis (see Chapter VIII). Under the terms of the Bubble Hypothesis, the flange glass flowed from the top (= posterior) to the bottom (= anterior) surface, whereas the Aerodynamical Control Theory requires flowage from the front (= anterior) towards the back (= posterior) surface, in the equatorial regions of which, flanges are built up. The internal flow structures of the flanges in relation to those of the body portions of australites possessing flanges, most definitely favour the Aerodynamical Control Theory, and provide additional evidence against the Bubble Hypothesis. Furthermore, friction and drag effects generated during phases of ultra-supersonic, and later of supersonic speeds of flight, seem adequate to explain the sculpture of the anterior surfaces of australites, inasmuch as turbulences brought about in a two-dimensional boundary layer flow of the atmosphere in contact with the australites, in addition to skin friction and form drag, would be created under these conditions. It is scarcely possible that such controlling influences could be generated under the terms of any theory advocating a terrestrial origin for such tektites as the australites.

Next, the Aerodynamical Control Theory should experience no difficulty in explaining why larger, core-like australites are non-flanged, while smaller button-shaped forms possess flanges, and still further, why the smaller lenses are non-flanged. It has been calculated (Baker, 1956) that to form a flanged button-shaped australite, over one half of an original sphere has to be ablated away, and approximately 7 per cent. has to be moved around as plastic or fluid glass to equatorial regions and there preserved as a flange. Something over 80 per cent. of an original sphere of tektite glass has to be ablated before the residual end product such as the lens type of average size can be developed. The causes leading to flange formation have already been put forward under the terms of the Aerodynamical Control Theory, but a few relevant facts remain to be added. It is obvious that, because of its steep forward curvature, and its exposure to greatest frontal pressures the forwardly facing hemispherical half of a sphere of australite glass, can provide no stable position for accumulation of flange-forming, secondarily melted glass. The earliest formed newly melted glass would be rapidly whipped away under the influence of drag effects, and as the process of fusion stripping and ablation progressed, there occurred gradual reduction of the front surface. Only after the front surface had receded so that its front pole was now near or had passed beyond the centre of the original sphere of australite glass, did a stable position for flange-glass-accumulation become available. Such a position is represented by the typical button-shaped australite (cf. Plate X, fig. A), where the arc of curvature of the anterior surface is much flatter than that of the front surface of the original sphere, and where a less steeply sloping portion of the primary rear surface is nearer at hand for flange glass accumulation. In this position, under the influence of eddy currents and some friction created by the separating boundary layer flow, the secondarily fused glass that had migrated to equatorial regions, began to cool and be moulded into shape. In most specimens, a buffer of turbulent air reflected from the cold posterior surface in these regions, was possibly responsible, associated with the degree of viscosity of the secondarily melted glass itself, for preventing the flange glass from spreading too far over and in contact with the glass of the cold posterior surface. In some specimens where spreading out of secondarily melted, potentially flange-building glass occurred, as in the manner of Fenner's "crinkly tops" (Fenner, 1934 and 1940), the secondary melt glass was evidently too fluid to be held back in the overhanging manner shown by the flange in Plate X, fig. A. The posterior surfaces of the flanges were located in low pressure regions during high speed earthward flight, hence these posterior surfaces are characteristically relatively smooth and often slightly concave.

The anterior surfaces of australites, were conversely situated in high pressure regions, and their equatorial edges where the flanges were produced, were positions of greatest frictional drag. Thus the convex anterior surfaces of the flanges typically reveal complexly wrinkled ridges and radial flow lines. All these features are consonant with a mode of formation by Aerodynamical Control, under conditions of high speed flight.

Further to the Aerodynamical Control Theory, a valid reason can be advanced to explain the variation of the specific gravity of flange glass as compared with the body glass of australites. Flanges have lower specific gravity values than the body portions to which they are attached (Baker and Forster, 1943), and this can arise as a consequence of the flange glass having undergone a secondary phase of fusion, during which some of the heavier, more volatile constituents were evidently lost, leaving a rather more silica-rich residuum of slightly lower specific gravity. Moreover, under the terms of the Aerodynamical Control Theory, the specific gravity values of the body portions of australites, remain as an essential function of their primary phase of formation in an extraterrestrial source, whereas if each australite had become completely fluid during atmospheric flight, it might be expected that the smaller forms would possess lesser specific gravity values than larger forms, because the more volatile constituents would escape during atmospheric flight, more being lost from the ultimately smaller than from the finally larger australites. In actual fact, it is found that in any particular part of the australite strewnfield, the smallest australites often have specific gravity values the same as those of medium to large size, and that both lower and higher specific gravity values occur among all sizes and among all shapes. It is thus evident that the specific gravity values of the ultimate secondary shapes of australites are not likely to be much different from those of the primary shapes, only inasmuch as small differences between flanges and body portions arise during supersonic flight; no changes are likely to result in the body portions themselves, since only microscopically thin frontal films of the fast-moving australites are fluid or plastic at any particular instant. On this basis therefore, it is concluded that variations in specific gravity among australites of different size, in each separate shape group found in different or the same localities, are primarily a function of their extraterrestrial phase of formation.

A further point to consider in connexion with the Aerodynamical Control Theory, is concerned with the all-important question of the temperatures generated in the cap of highly compressed and heated air between the front surface of an australite moving earthwards at ultra-supersonic velocity and the frontal shock wave situated a short distance ahead of this surface. It has been suggested (Baker, 1956), that temperatures in this cap of air may well have been in the vicinity of 2,000°C., because an effect of the intense compression generated by the formation of a frontal shock wave at ultra-supersonic speeds would be to considerably raise the temperature of fusion. The temperature at some stage of flight, must have been equal to the temperature of volatilization of australite glass, for the ablation processes to have operated under conditions where the temperature of melting was increased with pressure. Because of the limited time of flight through the earth's atmosphere, a few seconds to two or three minutes at most, there would be limited opportunity for reaction with oxygen in the atmosphere, most of that which was available would evidently be consumed during volatilization processes attendant upon ablation of certain amounts of australite glass in anterior surface regions. It is therefore not to be expected that outer oxidized films of glass would be extensively or continuously produced

on the front surfaces of australites during flight. Australites with oxidized front surface films have not been discovered in their natural state of occurrence on the earth's surface. Such films have been produced under laboratory conditions; after heating to 1,200°C. for two hours under atmospheric pressures in an oxidizing atmosphere in an electrically heated tube furnace, a flange fragment, a body fragment and a small button-shaped form possessing flange remnants, all developed reddish-brown skins measuring under 1 micron in thickness. This colour change indicates the conversion of ferrous to ferric iron in the outer skin of australite glass. If such were formed on front surfaces during flight, they were either removed by skin friction effects during a late stage of flight, or removed by weathering on the earth's surface. The indication is, however, that such films did not exist on most australites. Since the flange glass on australites represents secondarily fused material moved from front polar to equatorial regions at certain phases of secondary shape development, then flanges are the places to seek evidence for the possibility of partial front-skin oxidation during flight. Most flanges possess glass closely resembling that of the body portions of australites, and hence of uniform colouration. A few have been noted, however, which show colour bands in the flange structures (Dunn, 1912, p. 6; Baker, 1944, p. 12 and Plate II, figs. 1 and 9), and these colour bands are deep brownish, indicating that some oxidation of the front film had occurred, and that in these few examples, the oxidized glass became incorporated with the non-oxidized glass which forms the bulk of such flanges. During the later end phases of secondary shape development of australites, it would appear that such oxidation processes of limited production, had entirely ceased.

The writer has presented the above evidence in some detail in order to stress the possibility of the Aerodynamical Control Theory being a hypothesis capable of explaining the more important facts concerning australite shape and sculpture, and also as capable of explaining many minor features, some of which are dealt with elsewhere (Baker, 1955a, 1956). It has not yet been possible to extend the theory to embrace all other known tektites on the earth's surface, to which, in effect, it may not be so applicable. It does, however, seem a rational basis on which to found future studies of the Australian varieties of the tektites.

It seems that the development of the shapes of extra-Australian tektites has received no really serious treatment, apart from minor suggestions already mentioned in the earlier pages of this monograph. This state of affairs is partly brought about by other tektites not having the very special features possessed by australites. In bediasites, for example, it has been considered that the shapes as found, were controlled primarily by their original shape, and secondarily by the amount, depth and kind of etching and the amount of spalling to which they were subjected. A few distinct shapes such as lenses and teardrops have been recognized among the bediasites, but most forms are now ellipsoidal, a few nearly spherical, others very long for their thickness, and a few tabular, but no attempts have yet been made to explain the origin of these shapes in terms of modern theories relating to production from the primary forms that entered the earth's atmosphere from extraterrestrial space. The same applies to the other varieties of tektites from extra-Australian strewnfields.

CHAPTER XI.

ORIGIN OF THE SURFACE FEATURES (SCULPTURE) OF TEKTITES.

The origin of tektite sculpture is as controversial a subject as any branch of tektite studies. Some writers regard the surface markings on tektites as meteoritic corrosion, caused by factors operating prior to arrival on the earth. Others are convinced that the sculpturing developed while the tektites lay on the ground. A third group thinks the sculpture arose by a combination of the two methods.

As with the origin of tektite shapes, theories of sculpture formation on tektite surfaces are likewise intimately connected with various writers' views of tektite origin.

Among terrestrial theories of sculpture origin, the billitonite sculpture (Plate I, figs. A to E) has been regarded as due to gas bubble escape during dehydration of silicate gels (Wing Easton, 1921), but this theory has been effectively eliminated. Also unacceptable is the suggestion that the billitonite sculpture was produced during desert conditions that prevailed from Upper Jurassic to the end of Eocene times (Hövig, 1923). The evidence shows (see Chapter VII), that the billitonites had not arrived upon the earth's surface until after the close of the Tertiary period.

Percussion has also been suggested as the cause of the sculpture of billitonites (Verbeek, 1897), and some of the surface structures, referred to as "navels," have been considered to have formed by natural etching after percussion figures had been developed during stream transportation (Escher, 1925, p. 157).

A natural origin for tektite sculpture was condemned by Berwerth (1917), who believed that the sculpture of moldavites was of artificial origin, and that their surfaces were certainly not branded with 'the marks of heavenly origin'. Theories of an extraterrestrial origin for tektite sculpture were also rejected by Merrill (1911), who compared the surface markings with those on obsidian pebbles from Cali (Cauca Department) in Colombia, from Clifton in Arizona, from Marsh in Idaho, from High Rock Canyon in Nevada, and from Hrafntinnuhyggur near Myvatu in Iceland. Merrill claimed to have produced similar markings to those on tektites, by treating obsidian fragments with dilute hydrofluoric acid, and concluded that the markings on terrestrial obsidian more closely agreed with those on some tektites, than among tektites themselves, and therefore could not conceive tektite markings as having a common origin, nor as being formed through the same agencies. It was also claimed that the markings on Moravian, Bohemian, Australian and Billiton tektites did not resemble flutings on meteorites, and were simply structures on waterworn pebbles of weathered glass, originally etched by corroding vapours or solutions. It was also concluded by Wright (1915), that the furrowings on tektites could not be explained by means of fusion stripping.

The Corrosion Theory, advocating that the sculpture of tektites was developed while they lay upon the earth's surface, has been supported by Van der Veen (1923), Michel (1925), Lacroix (1931, 1932), Martin (1934), Beyer (1934), Rosicky (1934, 1935) and Fenner (1935a, p. 139). The sculpture of Philippine Islands and French Indo-China tektites (Plate VI) was regarded as secondary and due to chemical corrosion by humic and carbonic acids in the alluvial deposits of tropical countries (Lacroix, 1932), but at the same time, Lacroix also described angular and obtuse folded corrugations (Plate XVIII, fig. 5) on indochinites as being complicated by the motion of fluid glass, which

definitely militates against his corrosion theory of sculpture origin. Cylindrical or elliptical, undisturbed areas (Plate XVIII, fig. 6) in the middle of a confusion of wrinkles and flutings on some indochinites, correspond to already consolidated parts swept along in still viscous portions.

According to Lacroix' reasonings (1931b), the tails of most tear-shaped indochinites (Plate VI, fig. 6) consolidated just before landing, while contraction of later solidified portions on others, caused deviation of the tails from original positions, and their markings followed a similar course. Hence, narrow channels in drawn-out portions of the tails (Plate VI, fig. 9), anticlinal puckers (Plate XVIII, fig. 5), &c., are dependent upon the internal structure of the glass, but Lacroix thought they mainly represented deformations of the surface by chemical corrosion, and a similar origin was assigned to pitted surfaces bearing large and small cupules (Plate XVIII, figs. 7 to 10).

The deep surface sculpture of Indo-Malaysian tektites has been suggested as due to cracks, collisional bruising and subsequent etching in acid soils (Beyer, 1934). The nature of the etching was thought to indicate a great age for the indomalaysianites, because of the mild patination, in comparison, of Neolithic and pre-Neolithic implements made from these tektites.

Stressing the fact that groundwater was necessary to etch tektites, it was believed that tektites from the Philippine Islands (Plate XIX), Indo-China, Java, Siam and Bohemia were but slightly etched, while australites were not etched at all because they are found in desert regions where groundwater is in distinct shortage (Koomans, 1938, p. 64). Billitonites were regarded as being by far the most strongly etched because groundwater does occur on Billiton Island, and the presence of tin ore, topaz and tourmaline in Billiton was thought to have significance in pointing to a pneumatolytic influence. Since fluor was in the ground, it was argued that dilute hydrofluoric acid accentuated the stronger etching of the billitonites along cracks trending parallel to the original surface. The statement that australites generally occur in regions with desert climate is by no means correct. Australites are as abundant in temperate as in sub-arid and more arid regions. Koomans' statement conflicts with the frequent presence of superficial buckshot gravel in many areas of australite discoveries, because the buckshot is a clear indication of the presence of groundwater, as in numerous parts of the Western District of Victoria, where many australites have been found. There is little to support the idea that tektites are etched naturally by hydrofluoric acid in particular, since there are no indications of pneumatolytic substances in certain ground from which thousands of etched tektites have been collected in the larger tektite strewnfields. Moreover, in the tin-bearing regions of Australia such as the New England District, New South Wales for example, australites are not more especially etched than those from other regions very remote from areas carrying pneumatolytic minerals.

Markings on the bediasites have been compared (Barnes, 1940a, p. 501-503) with those on moldavites and those on obsidian from Iceland. Furrowing was regarded as an outcome of etching while tektites lay on the ground, because many spalled surfaces on bediasites were only etched 1 mm. and less, unspalled portions were etched uniformly to depths of 4 to 6 mm., so that Barnes contended that if furrows developed during flight, subsequently spalled surfaces would be without furrows. It seems to have been overlooked, however, that the bediasites are much older tektites than many others among the known tektite groups, and hence the fact that some spalled surfaces are only etched to shallow depths, could well be due to such surfaces having been exposed by

spalling long after their fall, thus presenting newer surfaces to the etching agents; unspalled portions have obviously been exposed to the etching solutions for longer periods without spalling having occurred, hence they have been more deeply etched along flow line directions. Such trends are even better shown among the younger australites, where variously etched " spalled " off fragments are sometimes scarcely etched, sometimes deeply etched, while completely preserved forms are frequently but little etched.

The markings on the moldavites have been compared with those on desert pebbles (" rilled stones ") from the Biskra Oasis (Abel, 1901, p. 25), and their origin ascribed to the attack of sand-laden air currents rotating in eddies. This was used as an argument for a like origin of the star-like markings on the disc-shaped moldavites, although it was thought at the same time, that the moldavite markings had not been developed in an arid climate. To begin with, the markings on " rillensteine " (" rilled stones ") have since been shown as not caused by sand-blast, and then the eddies would have to be very minute to produce such structures as " höfchen " and " tischchen " and the like, and there is no support at all for this postulate of tektite sculpture origin by sand-blast.

Some writers have considered the possibility of the surface features on tektites resulting on shrinkage of cooling glass. The " saw-cuts " on australites, for example, were supposed to be due to a peculiar type of shrinkage during cooling (Fenner, 1934, p. 68), or alternatively due to streaks of some soluble material being weathered out. Similar, deeper but broader crevasses on the Philippine Islands tektites (Plate XIX) were said not to represent shrinkage cracks as in quenched glass, and not formed after consolidation of the tektite glass (Hodge Smith, 1932, p. 582). It was assumed that these tektites were covered with a plastic coating in the earlier stages of cooling, so that differences in density and elasticity of the coating, led to the formation of crevasses where the outer skin offered least resistance to cooling. Actually, this is more like the nature of shrinkage and cracking observed when viscid Canada balsam begins to cool to the solid state. Frequent heating of commercial Canada balsam until it becomes dark brown and very stiff, followed by cooling, results in the development of deep, narrow cracks with parallel sides, that terminate in smooth, rounded ends as in most " saw-cuts " encountered on certain australites. However, it cannot be accepted that tektites were covered with a plastic skin, under the terms of modern theories of shape development, because such a skin would have to occur on both anterior and posterior surfaces of such tektites as the australites, and this would mean the ultimate production of the " crevasses " on both surfaces. In actual fact, such grooves as these are more characteristic of anterior surfaces of australites, i.e., the surfaces that were subjected to secondary fusion during atmospheric flight, and such fusion would eliminate rather than produce any early-formed " crevasses "; the grooves do not appear on australite surfaces until weathering and etching has occurred.

The sculpture of the Colombian glass spheres was also thought to be due to tension on cooling, as on obsidian (Friedlaender, 1927).

In the light of recent studies of the sculpture on the surfaces of tektites, it is considered that both extra-terrestrial and terrestrial agencies have played their part in first developing and secondly accentuating the flow patterns and associated features. It was originally thought that the surface markings on a piece of violet coloured artificial glass found with moldavites at localities near Trebitsch, meant that the markings on the moldavites were also due to chemical corrosion (Němec, 1933). It was shown later (Kaspar, 1938) that there were two types of sculpture present, (*a*) secondary micro-sculpturings due to chemical

corrosion in the soil, and (*b*) macro-sculpturings. The micro-sculpturings consisted of (i) hemispherical sculpturings, (ii) ellipsoidal sculpturings, (iii) incisions like deep wrinkles, and (iv) incisions like flat or shallow wrinkles, these all having been formed by some extraterrestrial means or during atmospheric flight, rather than by subsequent chemical corrosion in the soil from which they were gathered. Other writers have also contended that the markings on tektites were primary, and due to some type of meteoritic corrosion (F. E. Suess, 1900; Hanus, 1928; Oswald, 1935).

F. E. Suess (1898) who examined many hundreds of tektites, more particularly moldavites, disagreed with writers who advocated abrasion or weathering as the cause of the surface markings (see Plates III and IV). The markings were compared with *piézoglypts* (notch-like depressions or "cupules" formed on meteorites by air compression), especially the cup-shaped depressions resembling structures that Daubrée* had imitated by the action of compressed gases on solid bodies during dynamite explosions.

All markings on moldavites were considered by F. E. Suess as due to the results of enormous air resistances which produced sharper and smaller features than similar ones on iron and stony meteorites. Radially arranged rills on some specimens of the moldavites (cf. Plate IV) were regarded as marking positions where highly compressed air had torn open the highly heated masses of glass. Fine, brush-like marks on moldavites were thought to indicate that the specimens had not been abraded, and were developed later than cup-shaped depressions. Both the fine striae and the depressions were considered as having originated during earthward fall of the tektite glass. Critics of Suess' theory of sculpture development, contended that the markings he had described could well be due to chemical corrosion on the earth's surface, and in reply to this criticism, Suess (1914) agreed that some of the markings on the moldavites could have been due to such chemical corrosion, but he still maintained that this could not apply to the deep, long furrows. Suess pointed out that quartz and other pebbles, besides worked splinters of obsidian occurring in the same deposits as the moldavites, were completely unetched, even though they had been buried with them for thousands of years.

For the Paucartambo (?)tektite (Plate XIII, fig. 1) in particular and tektites generally, it has been contended that the surfaces were not instrinsically altered in the atmosphere, because flight duration and heating during this phase were too brief (Linck, 1926a, p. 172). The sculpture was attributed to the surfaces of the glass bodies having boiled, or to the corrasive activity of hot gases accompanying the tektites in a pre-atmospheric stage of earthward flight. It was subsequently suggested (Linck, 1934) that tektite sculpture developed upon some heavenly body, once close to the earth, but subsequently destroyed, or one which gave rise, such as the moon, to marked volcanic activity. According to Linck, the relief developed on tektites during expulsion from the heavenly body, was not destroyed during earthward flight, because tektites did not traverse the atmosphere at cosmic velocities, and heat of friction was thus insufficient to destroy the sharply marked jagged corners.

Differences in the character of the rear and front surfaces of australites, were thought by Hardcastle (1926) as not due to any adventure of a molten meteorite in conflict with a resisting atmosphere, but to the circumstances of their birth as independant objects, namely in their mode of separation as plastic sweepings from a melted meteorite. On this basis, pits would arise on

*—A. Daubrée—"Études Synthétiques de Géologie Expérimentale", Paris, 1879—Deutsche ausgabe von Gurlt, 1800—"Synthetische Studien", p. 514.

australite surfaces, because they would be "peppered with shot", chiefly of small gauge, fluid, and coming from the head of the parent meteorite from which plastic australite glass was swept. There are several objections to this rather fantastic idea, chief among which is the difficulty of producing pits on supposed plastic australites by "peppering" with small fluid drops, and the fact that on the basis of Hardcastle's theory, this "shot peppering" would have to arise in a very remarkable manner in order to "pepper" the rear surfaces of the australites, for it is a well-known fact that the forward surfaces of australites are seldom pitted and are characteristically flow-ridged, while posterior surfaces are typically pitted. The "plastic sweepings" theory would need to explain this situation by having the australites travelling back to front, and even then would not be capable of explaining why the posterior surfaces of the flanges of australites, being non-pitted, failed to become "peppered," while the posterior surfaces of the body portions took all the "peppering," and became highly pitted. The theory would also fail to explain why certain "swirls" on the posterior surfaces are free of pits, while immediately surrounding glass on this self-same surface is highly pitted. The theory of australite sculpture by Hardcastle's "plastic sweepings" method, is completely without foundation on fact.

Modern theories of the origin of flanges and flow ridges on australites have been dealt with in connexion with the origin of tektite shapes (Chapter X). Older ideas relating to their development are of passing interest. Berwerth (1917), who was convinced of the man-made nature of australites, suggested that their spiral flow ridges were due to a screw-like pressure movement applied artificially to softened glass. F. E. Suess (1914) regarded spiral ridges as indicating rapid rotation of australites during earthward fall. The writer considers that Stelzner (1893) was much nearer the mark in regarding these ridges as not due to rotation, but to air resistance that piled up waves or rings of wrinkles resembling those produced on the finger of a glove when being removed. Stelzner explained the streaks on australites as due to air action. Certain surface features he compared with those on meteorites, but concluded that the shape of meteorites was not regular, because they were solid, and only melted on the crust by the heat of compressed air, while "obsidian bombs" (i.e., australites) were plastic and easily distorted. The pits and scars on australites were regarded as not being due to gases escaping from the solidifying "bombs," nor to chemical corrosion acting in the locality where found, but were formed by aerial corrosion, in the same way as "thumb-marks" on meteorites. Differences in degree of development of pits, scars, furrows and striations were thought to have depended upon the viscosity of the glass of the "obsidian bombs," and the velocity of fall and strength of air resistance.

ORIGIN OF TEKTITE SCULPTURE BY THE COMBINED EFFECTS OF EXTRATERRESTRIAL, ATMOSPHERIC FLIGHT PHASE AND TERRESTRIAL CORROSION PROCESSES.

Based on the examination of many thousands of both worn and well-preserved australites, and on detailed descriptions of such tektites as the moldavites, indochinites, rizalites, billitonites and bediasites, it is the writer's opinion that tektite sculpture does not arise entirely from one single or simple process. The internal structures of tektites, as revealed by thin section studies, are obviously a direct result of their mode of initial generation as rapidly fused, rapidly chilled, primary bodies of natural glass that was relatively well-mixed but not entirely homogeneous, inasmuch as it contains flow streaks and minute lechatelierite particles. Such bodies must also have possessed an external flow

pattern, determined partly by gas escape and partly by glass-streaming in local patches less subject to gas escape (or to boiling) at a late stage in cooling. An initial external sculpture is thus envisaged as being closely associated with and related to the primary internal flow pattern.

In the secondary phase of sculpture formation, certain modifications of the forward surface of tektites that traversed the earth's atmosphere at ultra-supersonic and supersonic velocities, led to development of a few new sculpture features. In the australites, for example, radial flow lines were developed in thin films of glass streaming towards the equatorial regions of the various forms that possess flanges, while at the same time, flow ridges were formed and the flange ultimately produced. These features were controlled in their development by such processes as skin friction, form drag and turbulence. During the operation of these processes, different layers of the interior portions of the forwardly directed surfaces became exposed as ablation and fusion stripping progressed. Thus certain internal structures could influence the nature of the newly forming external features. For example, a lower layer in the tektite glass might be reached where internal small bubbles were present, and as these were exposed, their front surfaces would collapse, boundary layer flow would be upset, and concentric ridges could well take on an anti-clockwise or a clockwise motion as a result. In support of this suggestion, is the fact that wherever spiral flow ridges are observed on the anterior surfaces of australites, provided the specimens are still in a good state of preservation, there is usually present a small pit from one side of which spiral flow ridges appear to be generated. Such pits are not usually encountered on anterior surfaces with concentric flow ridges. It therefore appears possible that during atmospheric flight of australites, flow ridges may at one phase of development be concentric, then later may be spiral when such a pit is exposed by ablation, and may subsequently become concentric again with further ablation to levels of the front surface free of exposed bubble pits. Sometimes, these pits give the impression that they were not necessarily bubble pits, but that they could have been areas of rather more readily fusible glass, and hence would represent local etch pits, where the etching was an outcome of gas dynamics at high speed flight.

Other tektites do not possess the secondarily modified shapes of australites, and hence do not develop the secondary sculpture features outlined above. Hence it is assumed that their speeds of atmospheric flight were considerably lower; they were therefore not as highly heated, so that ablation apparently did not occur. They could have been sufficiently warmed, however, for processes of local fusion stripping to have occurred, resulting in the gouging out of grooves along certain pre-determined flow line directions where removal of tektite glass was facilitated because of slight compositional and minor physical variations.

It is considered that all tektites therefore arrived upon the earth's surface in possession of already pre-determined sculpture features. Most of these features were primary features, but some, as in the australites, were secondary features produced during high speed atmospheric flight. Under such circumstances, the australites possessed a secondary modified sculpture on the anterior surface which was vastly different from that of the posterior surface, the sculpture of the posterior surface being primary and unmodified by the airflow pressure and friction generated under the terms of the Aerodynamical Control Theory. The posterior surfaces of australites are thus regarded as remnants of initial primary surfaces as produced in an extraterrestrial source, and in this respect, they thus have something in common with all other types of tektites.

While on the earth's surface, embedded in surface soils or other superficial materials, all the different types of tektites were subjected to varying degrees of further modification by subaerial agencies that resulted in corrosion and corrasion. Being the youngest of all the tektite groups, the australites have been the least affected by such agencies. Chemical attack on the glass of tektites has accentuated certain fine grooves and deepened other grooves. Mechanical abrasion of specimens liberated from their environment in superficial materials and moved about by flowing water, has much modified and often almost destroyed the sculpturings. Specimens only recently liberated and little removed from their original sites on the surface, are infinitely better preserved but sometimes quite strongly etched.

There are various reasons why it cannot be accepted that chemical corrosion alone was responsible for the development of tektite sculpture. All the surface features of australites, for example, require something more than chemical corrosion for their production. To form bubble pits by chemical corrosion, would mean that considerable areas of the surfaces of tektites would have to be much more soluble than other parts, and such pits are not of a type produced by artificial chemical treatment. It is possible to accentuate fine flow lines on tektites (Plate XX, fig. E) by immersion in dilute hydrofluoric acid, but the effect is only that of slight differential solution along already present flow streaks. Recently broken surfaces of australites are smooth and glassy, but surfaces that were broken hundreds of years ago, are very much dulled and frequently display internal flow structures that have been brought out by a process of natural etching. It is scarcely conceivable that such structures as the flow ridges on australites could have been generated by chemical corrosion, for such structures would require some other, special control. Most of the larger and many smaller pits on the surfaces of tektites are evidently due to (i) bursting of small gas bubbles on posterior surfaces, and (ii) collapse of bubbles against pressure on anterior surfaces. Some of the much smaller, rather irregularly-shaped pits on some tektites may well be due to some degree of chemical etching. Then again, if chemical corrosion alone caused pitting on tektite surfaces, it is remarkable that posterior surfaces of body portions of australites are pitted, while posterior surfaces of the attached flanges mostly reveal no such pitting. It cannot be accepted that differential chemical corrosion would explain such a state of affairs. The conclusion is that terrestrial chemical agencies do not adequately account for any of the sculpture features of tektites, and the only part they play is in accentuating or otherwise modifying such features. The evidence available points to sculpture having originated largely in the original site of tektite formation and partly in the earth's atmosphere during varying speeds of earthward flight for the various groups of the tektites.

Chapter XII.

MOTION, VELOCITY AND FRAGMENTATION OF TEKTITES.

THE MOTION OF TEKTITES THROUGH THE ATMOSPHERE.

All the evidence so far adduced points to tektites having traversed the earth's atmosphere in one direction only. There is nothing to prove that they were thrown up to considerable heights from the earth's surface, later to re-descend after the fashion of volcanic ejectamenta. Tektites are therefore believed to have had a one-way translatory motion—towards the earth's surface. Several writers in the past have advocated that some of the tektites, e.g. the australites, also possessed rotary motion during their transit through the earth's atmosphere, the axis of rotation supposedly being parallel with the direction of translation. It was the opinion of F. E. Suess (1909) that the shape of australites indicated a motion of rotation while they were molten, but this view cannot be accepted unless one thinks in terms of the primary shapes from which the secondary shapes possessed by australites were derived. It has been shown in Chapter X, that the primary shapes of australites were those of the sphere, spheroid, apioid and dumb-bell, of which the sphere is not a form of revolution, whereas the remainder must have formed by rotation about an axis, and all these primary forms developed by rapid fusion, followed by rapid cooling in an extraterrestrial source, with no indications that such geometrical forms as the paraboloid and the annular torus were developed. Since spheres are only formed in the absence of rotation, there is no reason why they should start to rotate within the earth's atmosphere, after having entered it at ultra-supersonic speeds as cold bodies from outer space. All the modifications to which the primary, extraterrestrial forms of australites were subjected, are those which could develop on non-rotating bodies, and this applies especially to the parent forms that were initially produced by rotation, for the near spheroids, near apioids and near dumb-bells as now found in the secondary shapes of australites, are regarded as modified forms, the flanged forms with flow-ridged anterior surfaces being typically so. The writer cannot picture this type of modified form as resulting while molten in the earth's atmosphere. Surely a completely molten body of glass, travelling earthwards at very great speed, would be entirely dissipated, while a merely softened body of glass should become flattened and much distorted under similar conditions, whether rotating or not. The conclusion therefore is that australites did not rotate during the phase of transit through the earth's atmosphere, and the only motion present was one of rapid forward propagation, with possibly a little wobbling of some forms so affected by form drag as to be subjected to some degree of buffeting. Any rotation that had occurred during the history of tektite origin, was confined entirely to a very limited period in their extraterrestrial birthplace, and even then confined to not much more than 30 per cent. of the forms which developed as typical forms of revolution. Other forms of tektites are regarded herein as similarly having had no motion of rotation during atmospheric flight. Evidence in support of this conclusion has already been set out in Chapter X, while experiments conducted by Dr. E. S. Hills some fifteen or more years ago (Baker, 1958) prove that the shapes and features possessed by australites such as the button-shaped forms, can be produced from original spheres without rotation being imparted to them at any stage (see Chapter XV dealing with "Experiments with and relating to Tektites").

Among the indochinites, pear- and teardrop-shaped forms have been regarded as bearing eloquent testimony to a vertical fall, and as positive evidence supporting arguments in favour of a meteoritic origin for tektites (Lacroix, 1932).

In comparing such shapes with volcanic bombs, it was pointed out that volcanic bombs are bi-polar, while drawn-out indochinites are mono-polar. Furthermore, Lacroix believed that teardrop-shaped forms with long, slender tails and elongated parallel canals, could only be developed from a highly heated viscous fluid, the motion of which was that of vertical earthward fall without intense rotation. This theory is alright provided that the elongated indochinites are regarded as having their forms developed prior to the atmospheric flight phase, while in addition, the writer would prefer that the words " without intense rotation " should read " without rotation ". Again, these elongated forms of the indochinites, like those of the australites, were not completely molten during atmospheric flight, and inasmuch as they have not developed the secondary modifications produced on australites during transit through the atmosphere, it is believed that their speeds of translation were consequently much lower. There is an analogy, however, between the motion of each of these types during their descent to earth, for Lacroix has shown that the elongated indochinites fell with their long axes parallel with the direction of propagation. They thus possessed a similar position of flight to some of the teardrop-shaped australites, such as the " aerial-bomb " types (Fenner, 1934; Baker, 1956). It has recently been shown, however, that according to their modified shapes and structures, all the teardrop-shaped forms of australites did not have this kind of motion during atmospheric flight. Some, such as the example shown in figure 15, obviously adopted a stable position of translatory motion in which the longer axis was normal to the direction of propagation. Under such circumstances, with the accompanying ablation postulated herein under the terms of the Aerodynamical Control Theory, it becomes apparent that dumb-bell-shaped forms, which also had their long axes normal to the direction of propagation during atmospheric flight, could possibly develop into two tear-drop-shaped forms, if sufficient ablation occurred in the already constricted waist regions as to cause complete separation of the two bulbous ends. If this occurred, the two separate halves would then continue earthwards as independent bodies, still with their longer axes normal to the direction of propagation (cf. Baker, 1956).

It has been suggested that some tektites turned over during atmospheric flight, or that they slightly changed their direction, because rare examples of australites are known with flow ridges on both back and front surfaces (Fenner, 1934, p. 74). Inasmuch as the flow ridges are essentially characteristic of the anterior surfaces of australites, such forms must have presented first one surface, and later the other surface, to the aerodynamical phenomena operating to produce secondary melting and ablation on a forwardly directed surface. The only way such circumstances could arise, would be by turning over during atmospheric flight by chance collision with another australite; this would involve either overtake collision, or else meeting at a point where slightly different lines of flight intersected. In either circumstance, the collision would have to be of such a nature that the impact did not cause disruption of either form. The chances of such collision are rare, and so are specimens which present evidence that collision might have occurred during the phase of earthward atmospheric flight.

The presence of grooves along the whole length of certain forms of australites, has been interpreted as indicating an end-on motion through the earth's atmosphere (Fenner, 1934, p. 75). This applies to certain examples such as the " aerial-bomb " type.

The australites shown in Plate I, figs. H and N and in Plate X, fig. A, have grooves developed in the equatorial zone parallel with the flight direction, but normal to the long axis of the form which itself was normal to the direction of propagation; such forms therefore did not have an "end-on" motion.

VELOCITY OF TEKTITES.

The velocity of earthward propulsion of iron and stony meteorites has been calculated from such examples that have been observed to fall, but inasmuch as no authentic falls of tektites have been noted, there is no such direct evidence available for the rate at which tektites travelled to earth.

Among earlier theories of tektite origin, it has been postulated that australites might have travelled at 70 to 80 miles per hour at heights of 5 or 6 miles above the earth's surface, as bubbles with suspended blebs (Dunn, 1912b, p. 7). Fall to earth, on collapse of the thin glass bubbles, was suggested as being much slower, since the remains of each fractured pellicle were pictured as acting in the rôle of a parachute that gently floated australites to earth. The speeds suggested by this hypothesis are by no means sufficient to produce the secondary shapes and structures that australites possess.

Other writers have considered the possibility that tektites possessed cosmical velocities during earthward flight. The surface sculpture of moldavites was explained in terms of atmospheric corrosion due to fall through the atmosphere at speeds exceeding that of sound in air (760 m.p.h.), the velocities being compared with those of meteorites, variously estimated as between 20 and 30 miles a second, with a few estimates up to 40 to 50 miles a second (F. E. Suess, 1909). In discussing the origin of australites from a physical standpoint, a speed of fall to earth of 40 miles a second has been considered possible (Grant, 1909, p. 447). In studying the velocity of meteorites, it has been found that a disc-shaped tektite of 25 grams weight and 2·30 density, gave resistance to an air current travelling at 80 to 100 metres/sec. in a wind tunnel, of limiting velocity 53 metres/sec. (Maurain, 1931). Making certain assumptions, Maurain concluded that the limiting velocity acquired by the specimen falling through the earth's atmosphere, would increase with size, and some larger forms would accordingly arrive at the earth's surface with velocities of hundreds of thousands of metres per second.

From a study of the (?)Paucartambo tektite and its comparison with other tektites, the conclusion was reached that tektites did not enter the earth's atmosphere at cosmic speeds, for the reason that some specimens had a jagged relief, and it was considered that the heat of friction developed at cosmic velocities, would have melted all sharp corners, as in stony and iron meteorites (Linck, 1934). In australites, this argument does not apply, because any specimens that may show jagged relief, only do so because they have been subjected to fracture and etching on the earth's surface after their fall to earth. The complete forms of australites show all the earmarks of the production of secondary anterior surfaces, flanges and the like, as a consequence of prevailing high speeds of translation through the atmosphere, at times modified in their form by fusion stripping in equatorial regions. Ultra-supersonic and lesser supersonic speeds certainly seem to be necessary to account for the development of certain structures of australites, as outlined in Chapter X.

FRAGMENTATION OF TEKTITES.

Evidence exists that certain tektites were fragmented during the phase of atmospheric flight. Some pieces of indochinites have been regarded as due to bursting in the air while fairly soft, inasmuch as fragments shed from sizable spheres have been found, which possessed one end curled up or squashed in a manner indicating deformation after the original sphere had shattered (Beyer, 1934). Fragments of indochinites that show no such deformations, were shattered when hard.

A few australite fragments from the Port Campbell district of south-western Victoria, also bear signs of fusion and flowage subsequent to becoming separate entities, and rare examples have developed incipient flange-like structures. This can only have occurred during atmospheric flight. The theory of lens-formation by flange-shedding from button-shaped australites, as advocated by Fenner (1934, p. 66), also provides evidence of the fragmentation of tektites during flight, unless the whole of all flanges so shed are to be regarded as having been dissipated by ablation.

Many tektites have been fragmented while resting upon the earth's surface, some during stream transportation, some possibly by the force of impact on landing, as solids, on harder portions of the earth's surface, others as a consequence of diurnal temperature changes. A few of the australites could possibly have been abraded and cracked during utilization by large native birds as gizzard-stones, and some show " carry polish " attributed to constant handling by aborigines in the practise of their customs and rites. One or two from the Port Campbell district of Victoria, were accidentally fractured by cart wheels or horses' hooves, such specimens having been found on old roads last used in 1933. Others from sundry parts of Australia, have been deliberately fractured by aboriginal man in the manufacture of stone weapons and implements (Baker, 1957).

Some of the smaller core-shaped australites are conical in shape, and seem to have resulted from flaking and fragmentation of the equatorial portions of the secondary shapes by a tertiary process. They have been ascribed to flaking away of flanges and adjoining portions of button-shaped australites, caused by tension in the rapidly cooled glass itself, and aided by extreme temperature variations in desert areas, by bush fires and grass fires, and by percussion. The conical cores are the more stable end products of such processes, and several stages have been found (fig. 37) in the transition from button-shaped, oval-shaped, boat-shaped, &c., forms, the partly flaked shapes so developed being referred to as " indicators " (Fenner, 1935a, p. 130).

Undoubtedly compressive and tensional strains in not completely homogeneous (i.e., flow-lined) portions of tektite glass, play an important part in the ultimate fragmentation of australites, for even a scratch on the surface of highly strained glass may lead to its disintegration (cf. Rupert's Drops). The exposure of australites, over a long period of time, to various agents acting to different degrees while they lay upon the earth's surface, could affect their stability as shape entities, and it is a matter for surprise that a large proportion of complete forms can still be collected. Evidently these are forms in which the glass is not so highly strained, or else where strain is present, there must have been protection for a long time from any agency that could promulgate disintegration along stressed portions. The time element is also of importance here, for in comparison with many other types of tektites that are much flaked and spalled, the australites are relatively young tektites in terms of their time of arrival upon the surface of the earth.

The glassy nature of tektites makes them liable to ready fracture, so that in any collection of australites that has been thoroughly made, and all pieces of tektite glass as well as complete or nearly complete forms have been gathered, it is found that the proportion of fragments is relatively high, but this proportion varies somewhat from place to place, according to slight variations in conditions and according to the keenness of the collector. As an illustration of this variation, consider three australite collecting centres in south-western Victoria that have been scientifically studied in all detail—namely, the Port Campbell district, the Moonlight Head district and the Nirranda district, separated from each other by some 20 and 40 miles respectively. The proportion of fragments to complete or nearly complete forms in each centre is as follows:—1·55 : 1·0 for Port Campbell, 1·0 : 1·5 for Moonlight Head, and 1·38 : 1·0 for Nirranda. All centres were collected over by the same persons, so that the personal factor can be dismissed as contributing to these various proportions. The main factors are thus slightly varying conditions of preservation and release from the superficial deposits in which these australites occurred, and the numbers of australites

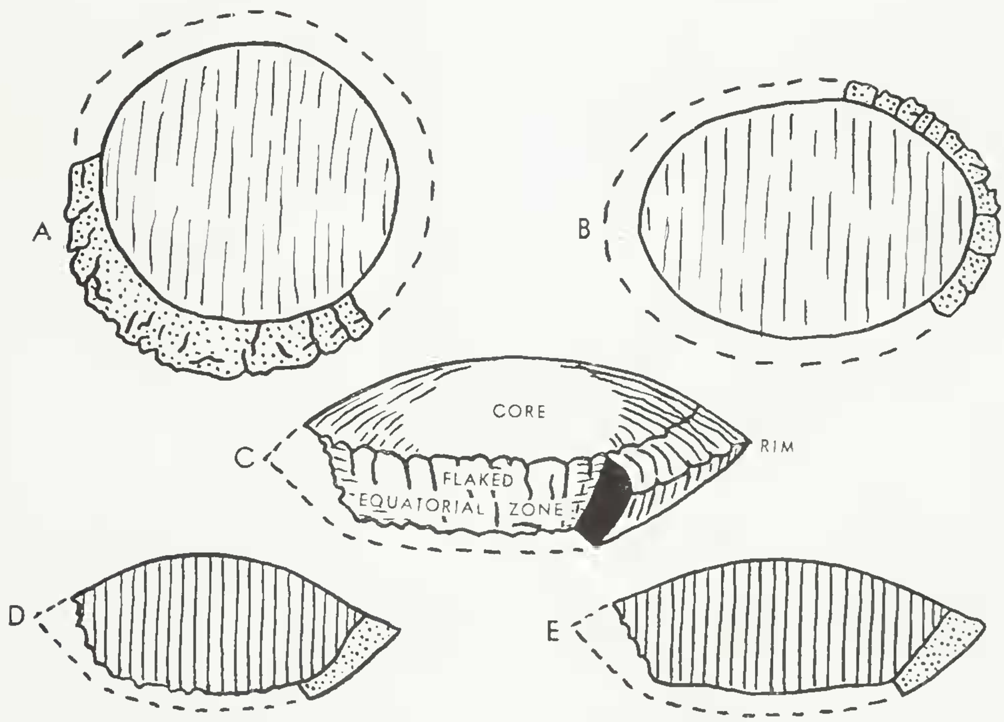

FIGURE 37.—Sketches showing one mode of fragmentation of australites. Broken lines indicate portions flaked away from peripheries. Stippled areas represent cracked equatorial regions still attached to the core portion (after Fenner, 1935).

found at each separate centre. The chances of fragments being formed were greatest in the Port Campbell district from where 1,500 specimens have been recovered, than at Nirranda where 400 specimens were found, and Moonlight Head where only 20 specimens were found.

The types of australite fragments found consist of pieces broken from the flanged equatorial regions of button-shaped and other forms, and hence revealing traces of the flange or of the flange band; pieces of the central core, often conical in shape; pieces from anterior surface regions and pieces from posterior surface regions of body portions of all shape types; fragments of flanges and occasionally

complete detached flanges; pieces from the tails of teardrop-shaped forms; half dumb-bells and pieces from hollow forms. Many fragments are of such a nature that the shape group from which they were derived, cannot be stated.

The result of fracturing processes of tektites is thus one producing various kinds of fragments of different size and shape, both from one and the same, and from different shape groups. Perhaps the most important causes of australite fragmentation and flaking are diurnal temperature changes associated with a pre-determined etch pattern. While buried beneath a superficial cover, many australites have flow-line directions accentuated and overdeepened on etching, as indicated in Chapter XI. On exposure of such specimens to the atmosphere by washing or blowing away of the constituents of the superficial cover, differential expansion occurs between quartz and clay constituents lodged in the etched grooves, and the neighbouring tektite glass, thus ultimately leading to the spalling away of certain portions of the tektite glass (cf. Baker, 1956), the shapes of which portions are delineated by the more prominent grooves.

The breaking away of complete detached flanges from button and oval-shaped australites, is largely controlled by differential expansion as between the tektite glass on either side, and sand grains and clay particles wedged in the gap region separating flanges from body portions. An important contributing factor is the relatively weak plane of contact present between body portions and attached flanges, for in such positions, the glass is thin and often the site of marked natural etching along the secondary flow directions, (cf. line of union between flange and body portion in Plate X, fig. B).

CHAPTER XIII.

USES OF TEKTITES AND THEIR VERNACULAR TERMINOLOGY.

Tektites are principally of scientific interest, but some varieties have had sundry uses.

On the Island of Hai-nan, where tektites are known as " excrèments d'étoile ", " crottes du diable " and " pierres de lune ", they have been used as charms and amulets by the natives (Patte, 1934).

Other Indo-Malaysian tektites, known to the natives as " taeng bituin " (" star dung "), " taeng kulog " (" thunder dung "), and " batong arao " (" sunstones "), as well as " moon-balls " and " devil-balls ", were employed by Neolithic and pre-Neolithic man for flaked implements and arrow-heads. They were also used by a pre-historic people of the Iron Age (500 B.C.), since those found in graves in the Philippine Islands show a characteristic " carry polish ", indicating their use as charms or amulets by the people of that time. In Indo-China, stone images dating from the early centuries of the Christian Era, were found with polished tektites set in the eyes of the idols. Tektites were also venerated in Indo-China by the late Bronze Age people. A lump of tektite glass discovered by M. Dalet in excavations on the archaeological site of Tûol Prah Théat, near Kompong Speu, was associated with ceramic fragments. This discovery is analogous with one at Prasar Trapéang Thual, north Cambodia (Lacroix, 1935a), and indicates the use of tektites by an ancient race of the Indo-Chinese. The ancient Khmers associated value and religious ideas with these natural glass objects.

The natives in Siam use tektites as " magic stones ", calling them " chanta " (" éclipses de lune " of Lacroix) and " kok pluak " (" termitières "). The first name is a survival of an ancient tradition, since the name is given to these objects by the natives of Pia Oac, Upper Tonkin, as well as by the natives of Borneo. The second name was probably inspired by the small hemi-spherical pits covering certain of the tektites. The Malays collect indochinites from the Smach district for jewelry purposes. Certain of the tektites in the East Indies are difficult to obtain because the natives on Bunguran Island (see fig. 2) for instance, seek them for cutting and sale as talismans.

One of the tektites from Solo in Java, appears to have been utilized as an arrow-head (Heide, 1939). South of Martapoera, Borneo, the natives call the tektites " hatou mĕloulout ", meaning literally " skin-cleaning scraper-stones ". One from Borneo was mounted in silver by the natives, and used as an amulet. The Malays believed that each malaysianite contained a gem; Scrivenor (1931) proved the theory wrong for a disappointed Malay rajah, by cutting open a specimen sent to him for the purpose of testing this belief.

Bediasites from Texas, U.S.A., known to local residents as " black diamonds " and " volcanic glass ", have been cut for jewelry sets (Barnes, 1940a, p. 495). There is no record that the Bedias tribe of the Indians were even aware of the existence of tektite glass, let alone of their having employed it for any purpose.

The so-called tektites from Colombia have been worked by the Indians (Friedlaender, 1927). Known as " piedras de rayo " to the Indians, they were used for producing sparks (Stutzer, 1926). The Colombian glass spheres and broken fragments of them were so plentiful, that they were collected with the intention of use in bottle manufacture (Döring and Stutzer, 1928).

The moldavites of Bohemia and Moravia, known as "vltavines" to the peasants, and named by them from Vltava (the Czechoslovakian name for the Moldau River), were used as implements by cave dwellers in Palaeolithic times (about 25,000 years ago). Walking stick knobs up to two inches long and an inch thick, were prepared from large specimens of moldavites in 1787. Some jewellers cut, polished and facetted moldavite glass for use as an ornamental stone under the name of "pseudo-chrysolite" or "water-chrysolite". It was regarded as a gem material as early as 1826, when Sternberg (1826, p. 42) called it emerald. The material was proclaimed as a precious stone by Erdmann (1832, p. 35), while Zippe (1836, p. 26) in a lecture on Bohemian gemstones, mentioned the name "moldavite" as probably being due to dealers in Bohemian gems. Hundreds of thousands of moldavites were cut as precious stones or passed into collections in Bohemia (F. E. Suess, 1909). They are still treated as gemstones in some quarters (cf. Kraus and Slawson, 1939).

Ivory Coast natives regard the African tektites as an index of the richness of the containing auriferous gravels. The tektite glass fragments in the Ouellé subdivision, called "agna" by the Baoulés, are as rare as gold. Their presence is claimed to cause some of the natives great anguish, "as though they were slipping into some deleterious effluvium". They would become inanimate at the sight of the "agna", and the natives preserved these little black stones so precious in their sight (Lacroix, 1934b).

Australites have been cut, polished and mounted for use as mourning stones in brooches and rings (1914-1918 war), and as semi-precious stones in cuff-links and dress-studs. They have been variously referred to by white man as "obsidianites", "obsidian buttons", "obsidian bombs", "blackfellow's buttons", "petrified apricot-stones", "button-stones", "emu-stones" and "emu-eyes". Lacroix (1932) stated that they recalled the form of "fruits d'arachide" ("ground-nuts").

The earlier use of the term "bomb" was objected to by Walcott (1898, p. 23), because it was considered that this term conveyed the idea of a terrestrial volcanic body; there being no proof of such an origin, he preferred to call them "obsidianites". Even so, Campbell (1906, p. 22) referred to an "obsidianite" about ¾-inch across, from Lake Dundas in Western Australia, as a "volcanic glass button". The name "button-stones" was applied to australites by the gold diggers (Stephens, 1897) because smaller specimens resembled a button without a shank. Australites in Tasmania were known to alluvial miners as "fossil gum-nuts" (i.e. fossil Eucalyptus capsules), or as "fossil pods"; one was likened in New South Wales, to the elytra of a large beetle.

There are certain superstitions among gold miners that the presence of australites in auriferous gravels is a good indicator of rich alluvial gold (Fenner, 1938a). Even contemporary white men, like native goldseekers in the Ivory Coast region, thus consider tektites have certain magic powers. Australites are well known to gold prospectors in Australia, and specimens taken abroad are treasured even now by superstitious miners on the placer goldfields of the United States of America (La Paz, 1938). La Paz drew a parallel between the shape of a miner's panning dish piled up with wash-dirt, and the side aspect of a typical flanged, button-shaped australite.

Australites were revered as objects of magic and mystery by certain tribes of the Australian aborigines. Petterd (1903, p. 6) referred to them as "remarkable pellets of mystery"—they were even more so to the aborigines, who employed them in cures for sickness and bodily pains, as death-pointers and in

rain-making ceremonies. Some tribes used them as cutting tools. In modern times, the aborigine has traded australites with the white man for sweets, tobacco and money.

Different aboriginal tribes knew australites as " ooga ", " muramura " and " minjiminjilpara ", meaning " emu-eyes " and " staring-eyes ". The magical powers attributed to these objects, are brought out in the following accounts. Twelvetrees and Petterd (1897) recorded that the Coolgardie aborigines in Western Australia, used australites as charms, pressing them to parts of the body suffering pain. Tate (1879, p. 70) noted that the aborigines held australites in very high esteem, and recorded their " disease-curing properties " according to native customs. He included an account by Mr. Canham of Stuart's Creek, South Australia, who stated that among a number of stones he examined, was one (an australite) with a strange history. It was supposed to have been taken out of a native's breast by a " koonkie " (witch doctor). The patient's life was not saved by this act, because the " koonkie " of another tribe had greater powers than the one who " removed the stone ". The sick native died of diseased lungs, and all the " koonkies " in the country could not have saved him.

Aboriginal possessors of certain " obsidianites ", were supposed to bear charmed lives, and were also supposed to be able to cure sick persons of any affliction. They could bewitch their enemies or anyone with whom they had a grievance, tormenting them with all kinds of diseases, and finally destroying life itself (Walcott, 1898, p. 42).

Australites were frequently discovered on old aboriginal camp sites. Some of them were artificially chipped or rubbed, others showed distinct signs of hand-wear (Dunn, 1912b, p. 14). The Rev. John Mathew, who was well acquainted with aboriginal ways, stated that black stones were used in the practice of sorcery by the Kabi Kabi, Wakka Wakka and Gurang Gurang tribes of the Wide Bay and Burnett districts in Queensland. Certain of these stones were australites, called " mullu " and " minkom " by the natives, who found them in creeks and waterholes. A sorcerer was believed to contain a number of them in his inside, and carried one or more in his dilly-bag. When a native felt a sudden pain, he ascribed it to a " mullu " being thrown at him by an enemy. They were used to make an enemy ill, or were thrown in the direction of an offending tribe, with a request to punish it with toothache. If, next day, the stones were found where originally picked up, it was believed they had fulfilled their mission. The Gippsland blacks in Victoria, used an egg-shaped stone called " bulk " (and said to be an australite), the owner of which was supposed to be able to cause death, merely by touching with it.

These stones had a curative as well as a lethal application. A heated spear-thrower was applied to the cheek of a native with toothache, the spear-thrower was then cast away, the toothache went with it in the form of a black stone (australite) called " karriitch ". Sometimes the black stones were placed in a long bag made of rushes, which was fastened around the cheek for the purposes of curing toothache. The native doctor always carried some of these black stones with him, and lent them to sick members of his tribe without fee or reward.

Among a collection of Australian aboriginal relics in the British Museum, London, a box of australites is labelled—" obsidian bombs, called by the natives ' mappain ', and worn applied to the stomach as medicine " (Fenner, 1939, p. 16)

Three australites in the Ethnological section of the Perth (Australia) Museum, are displayed, among other objects labelled as " Medicines and Charms ", as so-called magic stones (" mabbin " and " emu-stones "), used for curing

wounds, diseases, &c. Occasional larger, plate-like pieces of oval outline, were used in the religious rite of circumcision, and were sometimes used in the operation of sub-incision. One from the Nullarbor Plain bears the aboriginal name of " nyooloo ", but the meaning is not given. No arrow-heads made from australites are shown, but an example from Red Hill, Western Australia, is a chip of an australite, worked and used as a knife by an aborigine; it is approximately one and a quarter inches long, five eighths of an inch broad, and 1 to 2 mm. thick.

One of the very practical uses to which australites have been put by aboriginal man in recent years (and by his forefathers), is concerned with their food-hunting methods. Mr. H. R. Balfour of Toorak, Victoria, who made enquiries among the natives of the Woomera region of Central Australia about the reason for their use of the term "emu-stones," informs me that these aborigines wrap up australites in balls of emu feathers which are then thrown in the direction of flocks of emus. The particular natural inquisitiveness with which the emu is especially endowed, results in a close approach to these objects for near inspection and extraction of the contained australites. While absorbed in their investigations, the emus are speared by the aborigines. It has been found that the gizzards of emus often contain a number of stones up to an inch or so in size, usually of black colour, and a large proportion of which are frequently australites.

Scientific Use of Tektites.

Apart from the fact that tektites offer a challenge to man to make attempts at solving their origin, and as a consequence he has carried out many investigations into their shape, composition, internal and external structures, &c., there are a few scientific uses for tektites.

Granted that so far, tektites have, and have had, their greatest application in native customs of primitive man, nevertheless civilized man used them as gemstones, as souvenirs, as display collections in natural museums, and as the material for academic studies. Moldavites are of some stratigraphical importance in the science of geology, for they are regarded as due to a single fall, and so are of geological value in the sediments containing them, because they have the same importance as index fossils (Janoschek, 1934). Others may yet prove of like value.

It has been suggested that the shapes of australites might have some future bearing on problems of stratosphere aeroplane flight (Fenner, 1935a, p. 132), because their flow-ridged anterior surfaces were impressed upon them during traverse through the earth's atmosphere. The writer is of the belief that australites will provide not only interesting, but also highly instructive information to the aerodynamicist in the budding age of jet-planes and supersonic flight. Although this study is probably one that would be highly complicated, if seriously dealt with in terms of gas dynamics at ultra-supersonic velocities, by research workers most competent to carry out such studies, it appears to the writer that important information can be gained concerning the nature of frontal shock waves at very high velocities, the shape and position of such shock waves in relation to the front surface of the fast-moving objects, the nature and effects of temperature rises behind the shock wave on the front surface, and the degree and effects of skin friction in the boundary layers, cf form drag at high speed flight and any consequent buffeting, as well as the effects and consequences of turbulent flow from equatorial regions and the presence of the region of dead air behind the rear surface.

CHAPTER XIV.

ANALOGOUS STRUCTURES AND MATERIALS. PSEUDO-TEKTITES AND "AMERIKANITES".

Numerous natural and artificial materials have shapes, structures, and sculptures in some way or other similar to those of tektites, more especially worn or fragmented tektites. Some natural materials resemble certain tektites so closely in some features, that they have often been mistaken for them, and have been grouped as "pseudo-tektites" by some writers.

NATURAL MATERIALS RESEMBLING TEKTITES.

Some of the earlier writers on tektites were obviously impressed by their similarity to certain of the volcanic materials known at that time. The oval-shaped, flanged australite that Darwin (1844) examined, was considered by him to be one-half of a volcanic bomb, and closely similar in structure to balls of lava described by M. Bory* from the Isle of Bourbon, and to bombs observed (by Darwin himself) from Ascension Island.

An analogy on likeness in appearance, was drawn between certain australites and a bomb of obsidian from Mexico, sent to Stelzner (1893) by H. Rosenbusch. Both showed two differently curved surfaces and fine striae called "delicate brush-marks" of the atmosphere.

Many furrowed lumps ("blocs sillonés") of glassy material referred to obsidian, found by Beudant (1818, p. 214) in the high mountain region of Patko in Jugoslavia, were thought to have features resembling certain tektites; they were sometimes ovoid, swollen in the centre and terminated sharply at the two extremities. The regular surface furrows trend perpendicular to an axis of probable rotation. Large furrows are often intersected by smaller ones, and sharply defined crests separating neighbouring furrows are most irregularly lacineate. Beudant explained these structures by assuming an igneous origin and by supposing that vitreous material was hurled out in small pasty masses that developed their forms and structures by rotation in the air.

Pelée's tears, formed from escaping jets of gas spurting through molten lava, have been regarded as allied in shape and lustre to some tektites (Moore, 1916, p. 53), but the analogy of shape, as far as australites are concerned, is with their primary forms, rather than with the secondarily developed shapes as found. Chapman (1929), also considered that the shapes of Pelée's tears could be matched with those of certain australites.

In australite collections examined by Fenner (1934, p. 72, &c.), a small proportion of the specimens purported to be tektites by the collectors, were really fragments of dark-coloured rock, lydianite, pieces of hard charcoal, small pieces of well-polished limonite and dark-coloured hard-skinned plant seeds. In other collections, foreign bodies believed to be tektites by the collectors are actually sand-blasted, partially polished limonite or maghemite of the buckshot gravel type, waterworn dark-coloured chert and other fine-grained, dark-coloured, homogeneous rock fragments.

Substances with either deceptive shape, sculpture or colour resemblances to tektites, observed in the Port Campbell concentration centre of the australite strewnfield, include round dark blebs of resin from partially burnt grass trees

* "Voyages aux Quatre Isles d'Afrique", tome 1, p. 222.

(*Xanthorrhoea*), beetle cases of various sizes, abraded fragments of dark-coloured bottle glass, pieces of tachylyte (aboriginal chippings), waterworn pebbles of hornfels and flint, and dark-coloured, somewhat rounded, small nodules of magnetic buckshot gravel (maghemite) and non-magnetic buckshot gravel (dark limonite).

A chemical analogy between acid volcanic rocks and australites, advocated by Dunn (1914, p. 323), was shown to be incorrect by Skeats (1915a, p. 333). Dunn claimed that an early Victorian Geological Survey analysis of glassy rock from Taradale, Victoria, showed it was obsidian similar to australite glass in Victoria, and it was therefore deduced that australites were associated with Newer Volcanic (late Cainozoic) rocks. Skeats showed that Dunn's evidence was based on an unreliable chemical analysis, and the Taradale rock was not obsidian. It contains globulites, trichites and scattered phenocrysts of olivine, augite and plagioclase felspar. Skeats also proved the so-called "obsidians" from the Geelong district, Victoria, were tachylyte, an opinion previously held by Walcott (1898, p. 32). Skeats' work on this matter is an excellent example of the good use to which the petrological microscope was put some 40 years ago, to eliminate some of the incorrect ideas held, largely on the basis of opinion only, concerning the nature of certain natural glasses, including tektites.

Some perlites from Globe, Arizona, resemble tektites, but are readily distinguished from them under the microscope (Barnes, 1940a, p. 511). Etching along lines of strain, shrinkage cracks and lines of bubbles in obsidian from Hrafntinnuhryggur, Iceland, resembles etched structures in moldavites (Wright, 1915, pp. 279–280). For this reason, Wright supported Merrill (1911) in his belief that the external markings presented evidence against the necessity for considering an extraterrestrial origin for moldavites. The writer regards this as further evidence of the need for caution in interpreting a common origin for different materials, purely and simply because they possess certain features of similarity.

Percussion figures developed on a pebble of quartzite during river transportation have been regarded as resembling certain surface features of billitonites (Escher, 1925, Plate 1). This is not surprising, in view of the fact that the billitonites examined by Escher may well have been water transported. Several abraded, stream-transported australites, from which original flow patterns have been removed and the surface dulled, show similar percussion figures, mainly of the lunate chatter-mark type, obviously developed by impacts during rolling along stream beds, and thus unconnected with the original sculpture.

At Seleska in the Presov-Tokaj mountains, Eastern Slovakia, outcrops of perlitic and other types of obsidian have been found with surface features somewhat like those on moldavites and billitonites (Rosicky, 1934). This type of sculpture was thought to be due to weathering and thus supported the theory that sculpturing on tektites was due to chemical corrosion by atmospheric agents. It has already been discussed (see Chapter XI) how chemical corrosion can accentuate but not originate the flow patterns already present on tektites, and the same would necessarily apply to flow-lined obsidian glass.

ARTIFICIAL MATERIALS RESEMBLING TEKTITES.

A piece of violet-coloured glass weighing 3·12 grams, with a density of 2·626 and a refractive index of 1·548 (probably artificial) from near the moldavite localities at Trebitsch, Moravia, has been observed to possess surface

markings resembling tektite sculpture (Nemec, 1933). Such glass has obviously been etched under similar conditions to the nearby moldavites, and more soluble streaks have been removed rather more readily.

The shapes of australites have been compared with shot globules produced when fluid lead is dropped from a tower or into a shaft (Stelzner, 1893). These shot globules, however, have primary shapes, and hence the comparison should be with those of the primary shapes of australites prior to their entry into the earth's atmosphere. Some button-shaped australites have also been compared with the forms produced by firing a lead bullet into sand (Stelzner, 1893). Similar such forms arise when the bullets are fired against a metal target, and in them the softer front becomes flattened and bent back around the hard core (Plate XX, figs. A to C), thus resembling a flanged australite that is round in plan aspect, and hence more comparable with the secondary shapes of australites produced after high-speed traverse through the earth's atmosphere.

Small sphere-, oval-, dumb-bell- and teardrop-shaped glass blebs (fig. 38, A) found among glass-wool fibres (produced by passing powerful jets of steam through molten glass) have analogous shapes to what the primary shapes of australites and certain other tektites would have been. Similar forms are also developed in steel shot (fig. 38, B) and tin powder, but are less perfect than in glass wool.

Some of the forms found in glass wool show comparable flow-line structures, but none have the flange structure so characteristic of many australites. Others are somewhat bean-shaped, resulting from partial collapse of the narrower portions of glass in the waist regions and bending down of the bulbous ends of dumb-bell-shaped forms; such forms are comparable with bean-shaped australites.

" Slag-bombs " or " smoke-bombs " (fig. 38, C) emitted from the smoke-stacks of railway steam engines (exhibited by Mahcny (1910, p. 366) at the Royal Society of Victoria in 1908) are regarded by Fenner (1938b, p. 196, and 1940, p. 321) as resembling in many ways the forms of australites, but Fenner also thought (1938a) that these forms were perhaps more comparable with the shapes of Pelée's tears, and with some forms that are occasionally present among " impactites " from sites of meteoritic impact. Here again, the writer regards the shapes of the small " slag-bombs " as primary, and therefore comparable with the original primary forms of australites as produced at the site of their extraterrestrial birthplace. The " smoke-bombs " are composed of impure silica glass, are of microscopic dimensions, and sometimes contain minute bubbles of gas and occasional flow streaks. Similar minute siliceous spherules found in shore sands come from the funnels of coal-burning steamships.

Silica glass from burnt-out hayricks (" straw silica glass "), when compact (Plate XX, fig. D), has been sometimes mistaken for irregularly-shaped tektite glass. The more scoriaceous varieties are superficially like the silica glass formed in and around meteorite craters. Straw silica glasses are by no means related in any way to tektites; their content of potash (11·98 to 13·6 per cent) and soda (6·9 to 8·98 per cent.) is much too high (Table 23), among other things.

Glassy material found around a cratered and burning petroleum and gas well in Texas, U.S.A. (Barnes, 1940a, p. 512), is clear, deep bottle-green glass, in this respect resembling moldavites, although its refractive index is much higher than that of bediasites ($n = 1 \cdot 488$ to $1 \cdot 512$), and hence also higher than that of moldavites ($n = 1 \cdot 480$ to $1 \cdot 496$).

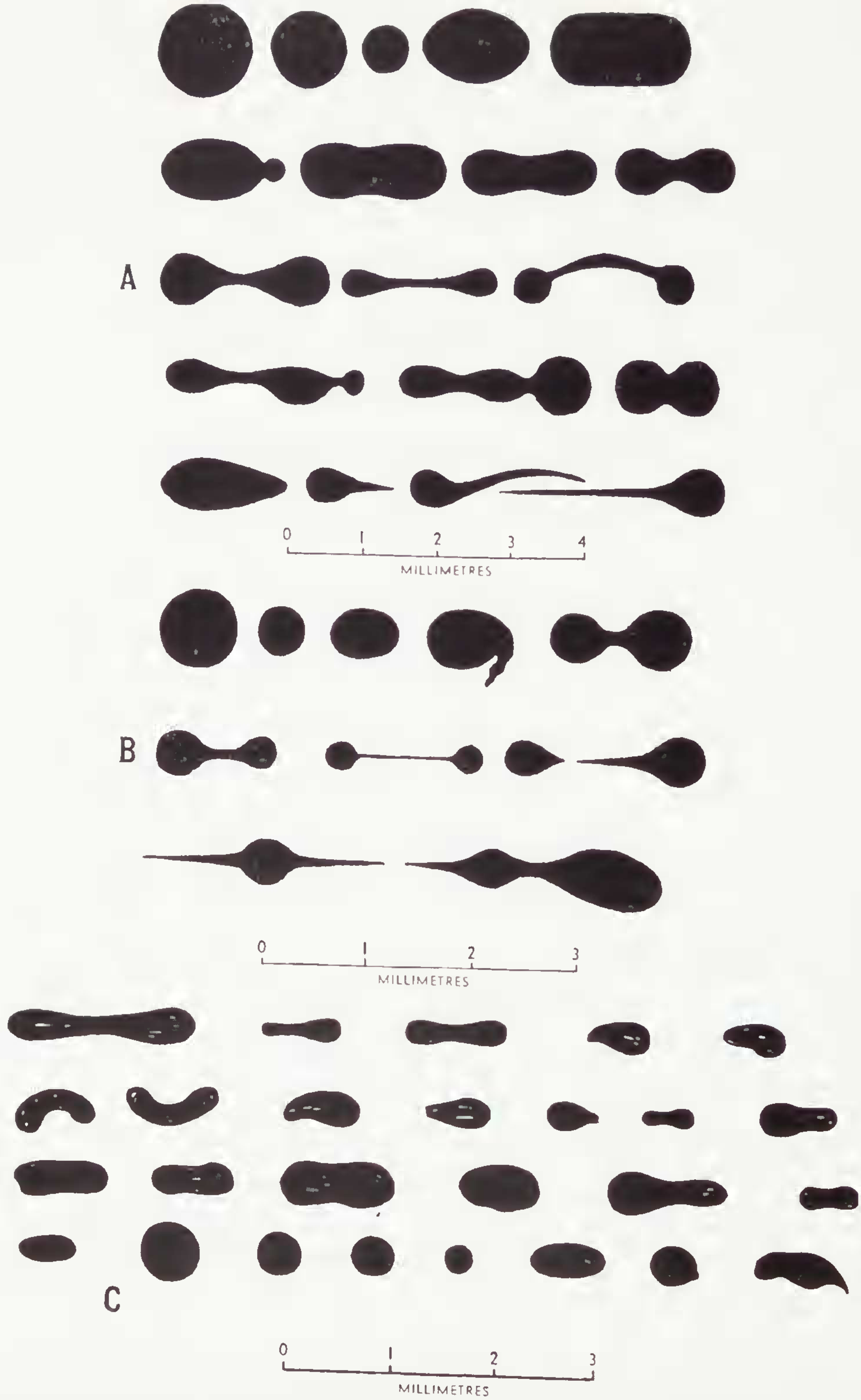

FIGURE 38.—Outline sketches of A—droplets from glass wool, B—steel shot, and C—"smoke-bombs" ("slag-bombs") having some shapes comparable with those of the primary forms of australites.

A parallel has been drawn between the shapes of "larmes bataviques" ("Batavian teardrops"—comparable with "Rupert's Drops"), with their gaseous inclusions at the swollen end of the tear, and pear-shaped indochinites with gas bubbles, from Tan-hai Island (Lacroix, 1932), and tektites have been referred to as "larmes bataviques" that had fallen from the sky (Belot, 1933).

Sculpture features resembling the sculpture of some tektites, resulted from the attack on flint glass objects by highly heated volcanic gases from the Mt. Pelée (Martinique) eruption of 8th May, 1932. These objects were eroded with pits and channels or burst bubbles of a very smooth, polished nature ("hot polish"), and it was thought that the secondary markings so produced, were suggestive of the external structures of some moldavites (Trechmann, 1938).

PSEUDO-TEKTITES AND AMERIKANITES.

Certain bodies referred to as "pseudo-tektites" resemble true tektites in either sculpture features or in superficial appearance (cf. Koomans, 1938). No specific definition of a "pseudo-tektite" has been given, and many writers consider that there is no justification for one. For present purposes, "pseudo-tektites" are regarded as inorganic terrestrial materials with superficial similarities to tektites, and they are dealt with herein for completeness only, and not because of any importance attached to "pseudo-tektites".

"Pseudo-tektites" correspond chemically to various terrestrial igneous rocks (Koomans, 1938; Baker, 1956a), mainly those of a glassy or partly glassy nature. Associated with the chemical differences that they show, there are also considerable variations in density and refractive index—properties that are largely functions of the silica contents.

Despite marked chemical, density and refractive index differences between tektites and many "pseudo-tektites" that are more readily discarded from consideration, there remains a minor group of materials with compositions so like those of tektites that their origin is very controversial. These comprise the so-called tektites from South America, occasionally referred to in the past as "amerikanites", similar materials associated with the true tektite strewnfields in the Philippine Islands, and valverdites from Texas, U.S.A.

Most materials resembling tektites superficially are readily distinguished by simple tests, but some require closer investigation for identification. Thus the true nature of dark-coloured glass (Plate XXI), occurring as twenty scattered fragments of irregular shapes averaging 1·5 to 2·0 grams in weight, collected from a duricrust surface on sand dunes at the Sherbrook River mouth, east of Port Campbell, Victoria, was finally shown to be allied to tachylyte by chemical analysis, although its character as a possible tektite glass was immediately doubted when its density was found to average 2·77.

Freshly broken surfaces of this material are glassy and show conchoidal fracture with secondary ripple fracture on the curved surfaces, as in tektites. Small pits, flow lines and grooves comparable with those on some tektites occur on surfaces with sub-vitreous lustre (Plate XXI). One surface feature not known on other terrestrial rocks has its nearest analogue in the "navel-like" structures (see Baker, 1956a) or "höfchen" and "tischchen" found on certain tektites, such as some of the billitonites. Such features are referred to herein as "ring-marks", which occur on a few of the glass fragments (Plate XXI, figs. 1 and 2). These peculiar "ring-marks" are sometimes isolated, occasionally coalesced to resemble a figure 8, or rarely arranged like short chains with

three or four links. Thin sections reveal an opaque glass, thus differentiating it from tektite glass. The glass in the ring-marks is light-brown, translucent and isotropic, with cumulose aggregates of the opaque glass, but no crystallites (see Baker, 1956a). The light-brown structures, which are ring-like in plan aspect and in thin sections, are actually shells enclosing spherical and ellipsoidal centres of the opaque glass. A partial analysis by Dr. A. B. Edwards at the Melbourne University Geological Department reveals a silica content (52·90 per cent.) well below that of accepted tektite glasses (68 to 82 per cent.). Lime (6 per cent.), magnesia (3·39 per cent.) and titania (1·27 per cent.) are all well in excess of these constituents in tektites. The analysis is nearest that of tachylyte among terrestrial rocks. No known examples of tachylyte from Victoria are quite like these glass fragments with their peculiar " ring-marks ", and none so far sectioned consist of such dark glass that even the thinnest parts remain completely opaque, like this glass from the Sherbrook River mouth. All the Victorian specimens of tachylyte examined under the microscope also usually reveal a content of small crystals.

Additional similar fragments of this black glass superficially resembling weathered fragments of australites occur along the coast of south-western Victoria, between Warrnambool and Peterborough, and have been examined in detail and shown to consist of a peculiar form of tachylyte of terrestrial origin, and evidently carried into these districts by aborigines (Baker, 1956a).

Koomans (1938) has recorded as " pseudo-tektites " deeply etched glass from Patagonia (density = 2·551), obsidian bodies (density = 2·330) called " pseudo-amerikanites ", and the *Claveria type* (density = 2·594) and *Luzon type* (density = 2·839) of glass found at Claveria and Luzon, North Philippines. Descriptions of some of these pseudo-tektites were previously given by Beyer. Many of their flow structures, flutings and pittings are said to resemble such markings on tektites.

Clinkers of wood ash, found in hollow tree trunks after forest fires at La Pine, Oregon, were described as the " tree meteorite " (Pruett, 1939, p. 150), and classified as " pseudo-meteorite ". Certain silica glasses previously classified with tektites, but now regarded with some considerable doubt, could possibly have had a similar origin to that of the " tree meteorite ".

From the descriptions of the " Queensland tektites " (Anon, 1937), it seems certain that the glassy material from the upper reaches of the Flinders River, Queensland, is not of tektitic character. Said to be of undoubted volcanic origin, and found only in the crater region, they consist of opaque, coloured glass, some light-grey with black spots, some light blue-green with yellow spots, some dark sea-blue with black spots, and others of dark brown colouration with black spots or inclusions that sometimes stand out above the surface of the glass. Some fragments also occur without spots or inclusions, and are cornflower-blue, dark olive-green and dark velvet-brown. The shape is that of jagged fragments, weighing up to 30 grams, hardness 6 and density 2·60. It is obvious that such materials should not have been classed as tektites, for their density is too high, and their colours are by no means those of the true tektites, but more characteristic of the coloured pieces of tachylyte known from certain parts of Victoria (see Baker, 1956a).

Coloured glasses like these are also recorded from the Philippine Islands (Beyer, 1940), Colombia (Stutzer, 1934) and Czechoslovakia (F. E. Suess and others).

Green "bottle-balls" 2 inches to 2½ inches in diameter, from India, have been included among the "bouteillenstein", i.e., moldavites (Kluge, 1860, p. 425). These glass balls possessed internal cavities about the size of a pea, and when one was sliced by a Paris lapidary, the unsecured half burst with a hissing sound and a detonation resembling bursting Rupert's Drops. The true nature of these "green bottle-balls" has not been established.

Specimens of glass sent to the British Museum of Natural History for identification, after the report of a meteorite fall near Quetta, India, seemed proof that at last a tektite had actually been observed to fall. The presence of iron wire in the glass, however, left no doubt that the so-called meteorite was really fused ash of a stack of bales of straw bound with iron wire that was struck by lightning and burnt (Prior, 1927).

Glass spheres from Kuttenberg and Oberkaunitz in Moravia, for some time regarded as tektites, created considerable discussion both in the local press and scientific literature at the time of their discovery. The fused surface sculpture of the Kuttenberg spheres was regarded as primary (Weinschenk, 1909), and the specimens showing this sculpture were thought to be genuine tektites. Other writers thought these spheres were not moldavites, but that they represented the residue from a glassworks (F. E. Suess, 1909); the sculpture was recognized as being different from that of true tektites, and was compared with the surface structure developed on ancient artificial glasses that had remained in the ground for some time, and were subjected to superficial decomposition (Rzehak, 1912).

The Oberkaunitz glass sphere was associated with glass pearls from Eiwanowitz and bronze objects on pre-historic graves. Chemically and structurally, the Oberkaunitz and Kuttenberg spheres are artificial glass, and there is no evidence for considering them to be of cosmic origin (Rzehak, 1912). Similar glass spheres from Krasna, near Wall, also proved to be non-tektitic (Rzehak, 1909).

One of the Kuttenberg spheres showed an equatorial region with a minute elevated flange and "latitude lines" parallel to it, another showed "schmelzrinnen", i.e., melting grooves (Weinschenk, 1908).

The Moravian glass spheres from Kuttenberg, Oberkaunitz and Netin were used as decorative objects on pre-historic graves. In certain quarters they were regarded as extraterrestrial glass, and different from glass spheres at Regensburg in Germany and Pardubitz in Czechoslovakia, which had the composition of normal antique glass, and were therefore from an ancient Roman glassworks (Weinschenk, 1911).

Controversial arguments regarding the true character and origin of the various glass spheres from Moravia have ended with the recognition that they are not genuine tektites, but artificial products. They may be regarded as "pseudo-tektites", in view of the fact that they were thought to be tektites for some time, because of sculpture similarities, but there is little doubt that the names "pseudo-tektites" and "pseudo-amerikanites" are really unnecessary introductions into the literature upon tektites. Once certain materials having certain features that could be mistaken for those possessed by tektites have been proved to be what they really are, and they turn out to be non-tektitic, there is no valid reason for changing their names.

The first recorded glass objects from Java, handed by the Regent of Japara to van der Ploeg in 1870, were found during the construction of an aqueduct, in deposits thought at the time to be either Pliocene or Quaternary (Heide,

1939), and one of these was described as having been ground and used as a charm (Lacroix, 1932). It is clear, yellow, contains a few gas bubbles, has a density of 2·512, and a refractive index of 1·531. Another example that had been partially ground was black in colour, with a density of 2·51 and a refractive index of 1·524. Of these two specimens, one was shown to be chalcedony and became relegated to the pseudo-tektite group, while the black specimen was thought to be a transported billitonite. The yellow variety was not accepted as a tektite by either Krausé (1898) or von Koenigswald (1935), for the latter had found in Java several yellow chalcedonic nodules with a tektite-like structure that had been developed by natural etching. After covering these etched nodules with Chinese ink and varnishing them, they appeared remarkably similar to true tektites. These so-called "cooked-up billitonites" were used as charms by the natives of Java, and such forgeries were said to be quite frequent (Heide, 1939).

The glass balls from Colombia and Peru, South America, named "amerikanites" by Wing Easton (1921), were not regarded as genuine tektites by most other writers, although some think of them as tektites. Because of their anomalous composition, F. E. Suess resolutely refused to accept them as true tektites.

The glass objects from the Philippine Islands that are comparable with amerikanites have been grouped as pseudo-tektites (Beyer, 1935), and described as bodies similar in general shape and surface structure to tektites, but with a chemical composition similar to terrestrial obsidian. Three types of these amerikanite-like bodies are recognized from the true tektite strewnfields of the Philippines, namely (i) a grey glass with the internal structure of ordinary obsidian, (ii) a brownish-violet to almost rose-pink, translucent glass of uniform consistency, distinguished from true rizalites only by their colour, and (iii) a greenish-yellow glass with the same glassy consistency and pitted surfaces as rizalites. The mode of origin of these so-called pseudo-tektites has not been solved, but Beyer was of the opinion that these "strange, new bodies" would have an important bearing on future studies of the tektite problem.

Some of the Philippine Islands amerikanites have been likened to the Colombian amerikanites, to Darwin Glass, and to moldavites, while others were likened to silica glass from the Libyan and Arabian deserts (Beyer, 1935).

The valverdites from Del Rio, Val Verde County, Texas, have been said to resemble certain australites (Cross, 1948, p. 154). A few hundred specimens of the valverdites were found on top of soil in an elliptical area 2 miles long and three-quarters of a mile wide, and they are far removed from any evidence of volcanic action. They range in weight from one-quarter of a gram to 32 grams, with an average refractive index of 1·48 and an average density of 2·30. They are opaque to translucent glassy objects, in places crystal-bearing and banded, and of a smoky amethyst colour where translucent. The valverdites have been proved to consist of weathered pebbles of obsidian, because of (i) their similar behaviour to obsidian under the blowpipe flame, (ii) their low densities and low indices of refraction compared to tektites, (iii) their content of crystallites and megascopic crystals, and (iv) other peculiarities (La Paz, 1948, p. 157). The valverdites are thus further examples of glass bodies that are not to be classed with tektites purely upon superficial resemblances. They are fundamentally different from tektites, and are allied to obsidian, in the same way that many amerikanites are allied to acid igneous glassy rocks.

Chapter XV.

EXPERIMENTS WITH AND RELATING TO TEKTITES.

A few experiments have been carried out with tektites, or with some readily controllable natural and artificial substances having certain suitable properties. These experiments were designed to simulate tektite shapes and sculpture patterns, or, when the tektites themselves were utilized, to ascertain some of their properties.

HEAT TREATMENT.

Various tektites have been subjected to heat treatment, and some have been investigated from this aspect in more detail than others.

Stelzner (1893) melted thin splinters of australites under the blowpipe flame to a glass free of bubbles. Gas bubbles were evolved after heating splinters for several minutes in a platinum crucible, and the glass became iridescent. When Moulden (1896) heated australite glass in a blowpipe flame, the glass was observed to soften without intumescence, and gave off no water on heating in a closed tube. The fusion temperature and the specific heat of australite glass was determined in the Physical Laboratory, University of Melbourne, as 1,324°C. and 0·21 respectively (Grant, 1909).

The writer (1956) has heated various complete and fragmented australites in an electric tube furnace to 1,200° C. for two-hour periods, under atmospheric pressures in an oxidizing atmosphere, in order to ascertain the effects upon the surface layers of these tektites. These australites, from Port Campbell and Nirranda in south-western Victoria, did not become softened except at one small place on one of the five or six specimens treated. This softening became evident by sticking to the containing silica boat at one small point. At 1,200° C., all the specimens treated had developed exceedingly thin oxidized films under 1-micron in thickness, and microscopic examination revealed that no particular strain phenomena had become evident in the glass immediately beneath this thin film, and the underlying glass was as densely black and vitreous as before heat treatment. The reddish-brown, oxidized film, however, was dull and somewhat iridescent in parts, occasionally with a satin-like lustre. The significance of these results has been set out in Chapter X.

F. E. Suess (1900) noted no complete melting nor colour change on heating moldavite glass in an oven. He recorded that J. A. Reich melted moldavite glass in a porcelain dish, but only at the highest temperatures possible in a glass furnace. Of numerous samples heated until plastic, and thrown into snow, only a small number cracked.

Linck (1926a, p. 159) heated a 1 mm. thick plate of the Paucartambo (?) tektite, and found that the glass softened at 800° C. Stronger melting occurred at 900° C., while at 1,000° C. a residual vesicular rock glass remained, having bubbles that exploded, leaving small round dimples like those on the outer surfaces of tektites. Bursting of larger complex bubbles resulted in sharp-rimmed depressions with smaller pits at the bottom. On further heating, the glass became intrinsically liquid at 1,200° C., but was still viscous, and gas escaped from it with difficulty.

Döring and Stutzer (1928) pulverized 140 grams of the Colombian glass spheres and heated the powder in an electric furnace. At 905° C. the glass softened, at 950° C. it became vesicular, developing many bubbles that increased

in number up to 1,000° C. This was thought to be due to the development of steam from enclosed chemically combined water and gases. At 1,085° C., melting commenced, and at 1,200° C. the process was complete; earlier formed bubbles decreased in size.

The temperature of collapse of a test piece 15·5 x 15·5 x 20·5 mm. of a Tan-haï Island indochinite heated in an electric furnace was determined under load (Lacroix, 1932). Pressure was transmitted by applying a determined static load, temperatures were determined with a platinum-platinum : rhodium couple, and rises of 500° C. in temperature were regulated at half-hourly intervals. Pressures of 100 grams/cc. were tried, and sagging commenced at 750° C. Similar treatment of a tektite from Cambodia, French Indo-China, furnished results of the same order of magnitude. Other heat treatment experiments recorded by Lacroix in comparing the behaviour of tektites from the various strewnfields of the world are recorded in Chapter III.

On repeatedly heating a plate of bediasite glass to white heat and plunging it into water, the only noticeable effect was the appearance of microscopic cracks around the edge (Barnes, 1940a, p. 507). Strain effects already present in the bediasite were not altered, and no secondary, superimposed strain pattern resulted. The conclusion is that flow structures in tektites were formed at considerably higher temperatures than was attained by heating to white heat before a blowpipe flame.

Barnes (1940a, p. 512) fused non-calcareous shale and also volcanic ash in a carbon arc, in order to compare the glass so formed with tektite glass. The writer has also fused non-calcareous sandy clay in a carbon boat for similar purposes. The glass resulting from each fusion contained lechatelierite particles in far greater numbers than those identified in tektite glass. The vesicularity of such artificially produced glasses contrasts markedly with the relatively bubble-free tektites; the shapes of the tektites were in no way simulated.

All experiments concerned with the heat treatment of tektites prove that tektitic glass has no fixed melting point; there is always a slow and gradual transition on heating, from rigid glass to fluid, with gas bubble evolution.

EXPERIMENTS ON SHAPE.

Experiments designed to simulate the shapes assumed by tektites have yielded some interesting and significant results. Some fifteen or so years ago, Dr. E. S. Hills, of Melbourne University, attached small spheres of paraffin wax to the ends of short wires bent at right angles, and placed them in a stream of hot water. Within limits, the pressure and temperature of the water could be controlled, and so the experiments were more readily conducted than by attempting to generate sufficiently high speeds on moving spheres to cause frontal melting. After short periods in the stream of hot water, the resulting shapes of the wax spheres had become astonishingly similar to australite buttons. Reduction had occurred in the amount of material at the front pole of the sphere, a small flange developed, and occasional though ill-defined flow ridges were formed on the surface confronting the hot flow stream. Because of rapid conduction of heat through the wax spheres, and because some hot water was able to flow around to the rear pole, the flow-stream being insufficiently strong to create a " dead " zone, many failures resulted because of slipping of the spheres along the wire rods. Nevertheless, the secondary shapes that were produced are significant in showing that shapes comparable to the secondary

shapes possessed by australites can be formed without rotation, and so these experiments lend strong support to the Aerodynamical Control Theory of australite shape development elaborated in Chapter X.

At the same time that the paraffin wax sphere experiments were carried out, the writer experimented with molten paraffin wax bodies, in order to ascertain whether the secondary shapes could be produced as readily or as well with completely molten material. Paraffin wax and turpentine were ignited in a small, shallow tin perched on a tripod-stand set in a large tray of water. The molten wax that was spluttered out in droplets had a short downward flight of approximately 1 foot from the burning mixture. The shapes produced during descent and upon the top of the water in the large tray were those of oval plate and round disc forms, evidently resulting from flattening on contacting the water surface. Such forms were not so unlike the flat disc-shaped and oval plate-like australites. Many forms were simply splayed-out spats, of irregular, flattened, cake-like shape, and of a type unknown among the australites. A few crudely button-like forms were also produced, but they possessed a very much flattened flange surrounding a convexly curved central core, but this core always consisted of a hollow hemisphere—in other words, there did not exist a convexly curved anterior surface. Forms due to revolution, such as spheroids, teardrops and dumb-bells, were not observed. These experiments indicate that the secondary shapes possessed by australites are best simulated by commencing with cold, solid primary forms, and heating their forward surfaces, rather than by starting with molten droplets.

Researches by Masanobu Tamura* revealed that paraffin drops were flattened on impact, developing forms resembling those arising from the impact of rifle bullets against a metal target (cf. Plate XX, figs. A to C). These forms resemble some of the flatter australite buttons, and hence raise the question of the possibility of a small, more or less plastic glass body being flattened by high-speed encounter with the lower, denser layers of the earth's atmosphere. Such forms as might have been thus flattened would, under the terms of the Aerodynamical Control Theory of secondary shape formation of australites, have to be thin forms at the stage of flattening (see Chapter X). It is extremely doubtful whether a flattening process could have occurred on impact of plastic glass with harder portions of the ground on landing, for such impact would surely destroy the perfect symmetry possessed by the flatter types of australites (round discs and oval plates). In addition, all the evidence points to the fact that australites were cold and solid on reaching the ground; had they been soft, foreign particles would have been embedded in the plastic forward surfaces that struck the ground, and such a phenomenon has not been verified in any australite specimen.

Professor C. V. Boys experimented with the discharge of electric sparks through molten resin, in order to imitate the shapes of tektites. Chapman (1933, p. 876) recorded that Boys produced many of the characteristic forms of australites, but did not state whether they were similar to primary forms such as spheres and the primary forms of revolution, or to secondary forms (i.e., modified spheres and modified possible figures of revolution). Chapman thought that Boys' experiments confirmed the theory of australite formation by electrical discharge during cyclonic dust-storms in Australia, but this theory has been satisfactorily eliminated (see Chapter VIII).

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* "An Experimental Research on the Form of Frozen Raindrops."

Thorpe (1913) attempted to manufacture glass bubbles in order to substantiate the volcanic Bubble Hypothesis of australite origin, and to see whether the bleb in such bubbles would occur at the upper or at the lower pole. Little success attended the experiments.

Hodge Smith (1932, p. 582) recorded how Mr. G. C. Clutton of the prepatorial staff, Australian Museum, Sydney, made a cast of one of the "islands" surrounded by a circular "crevasse" (i.e. = "tischchen" and "höfchen" of foreign writers) on the surface of a billitonite. The base of the casting was trimmed to the bottom of the crevasse, the cast painted black, with the resultant production of a "perfect" (but minute) australite.

The effect of angular velocity increase on the stability of molten bodies is indicated by the Plateau experiment (see Jeans, 1919). A globule of water and alcohol, mixed to the right density to float in olive oil, is set in motion by spinning a wire through the centre of the globule. The globule is kept in position on the wire by a disc round which it clusters. Increased speeds of rotation cause the globule to gradually flatten until a dimple forms in the centre, and the globule ultimately detaches itself from the disc in the form of a perfect ring. On the basis of this observation, one might be tempted to suggest that the detached complete flanges of australites separated in their entirety from the body portions during rapid rotational flight. However, if formed in such a manner, the complete detached flanges of australites would not be expected to have the smooth, slightly concave posterior surfaces and the wrinkled flow-ridged anterior surfaces which they possess, and moreover, such detached flanges invariably show signs of having broken away from body portions while in the solid state.

It is also worthy of note that rings of the type described in the Plateau experiment, and produced by rotation, can also be developed in other ways in which rotation plays no part. The writer has repeated experiments devised by Thord Brenner*, and although these experiments may have little bearing upon tektites, they do serve to show that certain shapes can be formed by other than rotational forces.

By dropping clay suspensoid from an orifice into pure water, shapes resembling certain australites can be imitated, as indicated in figure 39.

Clay particles smaller than 0·5 micron and free from electrolytic substances were well mixed in distilled water, and transferred to a tube 65 cms. long with an inner diameter of 1 cm. The orifice was 2 mm. in diameter. Rubber tubing with a screw clip, placed at one end of the tube remote from the orifice, was closed when the tube was partly filled with clay suspensoid. The narrow orifice of the tube, which was fixed in a vertical position, was immersed to a depth of 1 cm. in pure water contained in a cylinder 35 cms. deep and 7 cms. wide. When the orifice was first immersed, clay particles emerged as a discoloured current, while pure water rose up into the tube from the cylinder. With sufficiently strong clay concentration and a continuous, but gentle flow from the tube, the discoloured current constricted a short distance below the orifice. Elongated spindle-shaped drops began to form and decreased in size the further they fell from the orifice. At a certain distance from the orifice, the clay particles transferred from the core to the outer portions of the drops, leaving clear water inside, and at the same time resulting in shapes (see fig. 39) remotely simulating some australite buttons. The clay particles ultimately

* "Vattenomholjen kring Mineralpartiklarna", Mineraljordarternas fysikaliska egenskaper, Bull. Comm. Géol. de Finlande, No. 94, pp. 46–53, 1931.

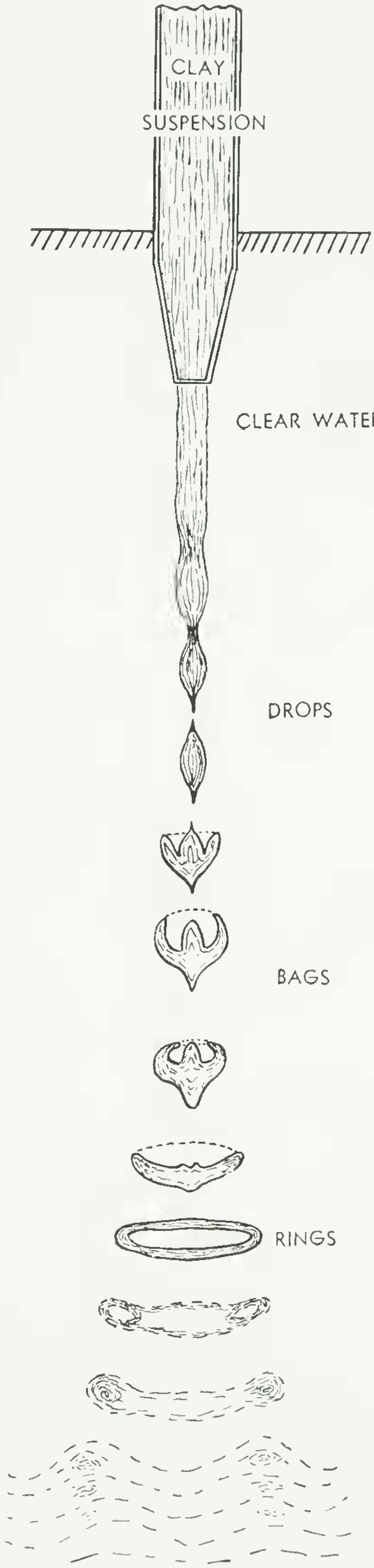

FIGURE 39.—Shapes formed by gently dropping clay suspension into clear water. Some shapes somewhat resemble certain forms and structures of australites.

formed into a ring, as in tobacco smoke rings, but gave no indication of the kind of rotation advocated by some writers for australite flange formation. The ring shapes resembled that of a flattened annular torus. The small bags of clear water left within, then dropped through the rings, creating minor turbulent motions. The particles in the rings rapidly dispersed on reaching the lower limits of the vessel into which the clay suspension flowed.

With smaller concentrations of clay particles, and the addition of a little glycerine, the rate of fall of the drops slackened considerably, and more numerous perfect rings were produced between 5 and 10 cms. below the orifice. Low concentrations such as used, also resulted in the rings oscillating back and forth through each other, mainly in pairs, rarely in threes and fours, before ultimate dispersal. Once commenced, the streaming out of the clay suspensoid continued even with the screw-clip tightly closed on the rubber tubing, until finally the whole of the clay particles were transferred into the receiving vessel, and clear water into the tube. Under this set of conditions, the shapes produced were as represented in fig. 39. When the clay concentration was too great, or when coarser particles were present, irregularly-shaped drops formed 3 mm. from the orifice and broke up speedily without forming the spindle- dumb-bell-, tear-, button- or ring-shaped structures met with in lower clay concentrations of evenly-sized, fine particles.

ETCHING EXPERIMENTS.

Several attempts have been made to accentuate the internal flow structures and external flow patterns of tektites by exposing slices and specimens to different acids of varying concentration. Dunn (1912b, p. 5) had no success on treating australites with hydrofluoric or other acids. The writer obtained negative results on immersing polished slices of australites for two months in concentrated HCl and concentrated KOH (Baker, 1940a, p. 491). Faint internal flow structures were weakly accentuated only after treating a polished surface for ten minutes with a mixture of strong sulphuric and hydrofluoric acids. Etching occurred along strain and flow line directions, where the australite glass was evidently slightly more siliceous. Dulled and abraded australites are best etched with 4 per cent. hydrofluoric acid (Baker, 1956). Specimens left in acid of this concentration for 64½ hours, at approximately 21°C., develop a fresher surface and lose the dull appearance they possessed prior to acid treatment. Differential etching initiated small etch pits above tubes of glass of slightly more acidic composition, slightly deepened the worn walls of bubble depressions, developed fine feathery streaks along some flow line directions, and deepened pre-existing grooves. Weighing before and after acid treatment revealed a loss of 0·397 grams of the tektite glass in 64½ hours. This means that acids responsible for etching under natural conditions must have been relatively weak, because they have had thousands of years in which to operate on tektites favourably situated for natural etching. These etching tests satisfy the writer that much of the external sculptures of anterior and posterior surfaces of australites, are purely and simply manifestations of the sub-surface, primarily generated internal flow patterns. A point of interest also brought out by these tests, is that anterior surfaces were no more etched than posterior surfaces, as far as the eye can judge. The significance of such observations, interpreted in the light of the Aerodynamical Control Theory of secondary shape development of australites, is that the secondary phase of melting and flowage experienced by anterior surfaces and flange structures, resulted in little change in the chemical and physical characteristics of australite glass as compared with posterior surfaces which were not subjected to a secondary melting and which

thus remained as remnants of the primary surface. The appearance of an australite at the time of its discovery, depends upon whether etching or abrasion had been dominant; abraded specimens have been exposed for some time, etched specimens have been under a cover protecting them from abrasion, but in places subjecting them to attack by weak acidic solutions.

It has been noted that HF etching produces markings on other tektites similar to their natural sculpturing (Van der Veen, 1923). The production of accentuated flow line structures on the Paucartambo (?)tektite by treatment with a mixture of concentrated HF and H_2SO_4 led to the conclusion that the natural etched appearance of tektites was produced by the strong, corrosive effects of accompanying hot gases during atmospheric flight (Linck, 1926).

Fine flow line structures have also been developed on an indochinite by etching with hydrofluoric acid (Lacroix, 1932). The results of this treatment are illustrated in Plate XX, fig. E.

Surface sculpture has been produced on both obsidian spheres and polished moldavites by means of dilute hydrochloric acid (Jezek, 1910), such sculpture, being thought to resemble the natural sculpture of both moldavites and billitonites. At the same time, the "varnish-like" lustre of tektites was produced in hydrochloric acid. Jezek and Woldrich (1910) concluded from these experiments that tektite sculpture must be due to chemical corrosion, and for this reason they opposed theories of a cosmic origin for tektites. Because tektite sculpture can be accentuated by chemical corrosion, however, is no argument against their ultimate extraterrestrial origin.

A naturally etched billitonite has been ground down until all original sculpturing was removed, and percussion figures were developed. On re-etching with strong hydrofluoric acid, the "navels" produced by percussion during grinding were reproduced exactly like those on natural specimens, and it was therefore concluded that sculpturings on billitonites were due to natural abrasion and etching (Escher, 1925, Plate I). Here again, the reproduced structures are to be regarded as manifestations of the internal structures of these tektites.

OTHER EXPERIMENTS.

Experiments have been designed by P. Hess (see F. E. Suess, 1900) to simulate the external markings on moldavites, by causing gases from explosions to impinge on lead plates, thus producing distortions and ridges, but no grooves other than occasional scars. Colophany (black resin) bodies were also used, because they behave like glass on melting, and exhibit properties at 130°C., that glasses do at far higher temperatures. Jets of dry steam at 300°C., under about 8 atmospheres pressure and 4½ inches wide were forced normally in some tests, at an angle in others, upon sometimes stationary, sometimes rotating colophany bodies. On rotating a colophany body 7·5 cms. in diameter, in which the exposed surface rose to a low cone in the centre, molten layers were produced, brushed off and renewed; drops of plastic material were torn away from the equator of the body. When the 4½ inch wide jet was 42 cms. away from the colophany body, small pits were produced, but when 10 to 20 cms. away, the edges of the body were melted off, and a network of fine ridges formed on the exposed surface. No spiral curvatures were developed in the ridges, even though the colophany bodies were made to rotate. On stationary amorphous colophany bodies, the effects of hot gas jets were centred around individual points, resulting in orderly rows of impressions (notches) like those on some moldavites. One of Suess' (1900) illustrations of these experimental results, can be matched by the posterior surface of an oval-shaped australite core from Tatyoon,

Victoria.* which shows remarkably well-preserved, fine and coarse radially arranged flow and "piézoglypt" structure (see Plate XXII). These occur, however, on the surface regarded as having faced away from the earth during atmospheric flight, and therefore must have been formed in a pre-atmospheric phase, probably at the site of tektite generation in an extraterrestrial source. Nevertheless, there are structures developed on the anterior surfaces of australites which are comparable with those produced in the experiments of Hess, and although these experiments did not inspire the Aerodynamical Control Theory elaborated in Chapter X, they have a distinct bearing upon some of the details of that hypothesis.

In connexion with the observations that most australites are found with posterior surfaces downwards, a position regarded as their natural, stable position of rest in the strewnfield, specimens were cast, with and without spinning motions, on to ground bare of vegetation, from a height of fifty feet. In 90 per cent. of these tests, the australites came to rest with posterior surfaces downwards, irrespective of the shape type used, and even though they were always cast with anterior surfaces pointing earthwards, i.e., the accepted and logical position of flight of australites through the atmosphere.

To test the nature of the fragmentation of tektites, australites have been tapped with a hard steel hammer on an anvil. Being brittle, they commenced to splinter under relatively light, repeated blows. With more powerful, sudden blows, equatorial portions spalled away, frequently in conchoidal pieces showing rippling. Flanges broke off quite readily, sometimes carrying small attached fragments of body portions with them, but no complete detached flange was obtained in these tests. One of the most significant types of fracture fragments formed, was a central conical fragment, identical with the numerous conical-shaped cores (Fenner, 1934, pp. 68 and 72) found under natural conditions. Concentric fractures, so common in other types of natural glass, as well as in australites and extra-Australian tektites, were regarded by Fenner (1934) as "the outward physical sign of an inward physical strain". Most conchoidal surfaces exhibit the secondary ripple fracture pattern. There seems to be no general rule governing the way that the flanges of australites break up, either during or after separation from central body portions. Those tested broke sometimes at right angles to their circumference, sometimes at an oblique angle, but never parallel with the outer or inner edges with which flow lines are normally parallel. Experiments on the fragmentation of tektites, makes one wonder why such examples as the australites did not all become shattered on impact with the earth's surface. The fact that there is no positive proof of flattening due to impact of plastic tektite glass with the ground, and every indication that they were entirely solid on landing, points to their behaviour during the end phases of atmospheric flight as having been comparable with that of most meteorites. When meteorites are no longer visible—if they have not burnt out—it is because they have cooled, lost their cosmic velocity, and instead of continuing along their original line of flight, they fell to earth at speeds controlled by the earth's gravitational pull. In view of their small size, the australites and other tektites were evidently decelerated considerably in the denser atmosphere near their points of impact with the ground, otherwise, being composed of brittle glass, they would have become fragmented considerably where contacting hard ground. Those landing on soft soil would stand less chance of fracturing. The fact remains that many australites are found in excellent states of completeness, while many fracture fragments often provide evidence of subsequent breaking up under the influence of atmospheric agencies.

* Specimen lodged in the Victorian Mines Department Collection.

CHAPTER XVI.

NATURAL GLASSES OF METEORITIC, LIGHTNING AND UNKNOWN ORIGINS.

Apart from tektites and objects called "pseudo-tektites", several examples of natural silica glass only distantly related to tektites in having been melted ("tektos" = melted), belong to a group of glasses of different composition, different physical characteristics and different general appearance. Their mode of formation differs radically from that of the origin of tektites, and so they are treated as a separate class. They are included in this monograph because of the comparisons that have been drawn between the mode of origin of these silica glasses and those of some of the tektite silica glasses.

Silica glasses so far recorded are known from Köfels in Tyrol; Odessa in Texas, U.S.A.; Wabar in Arabia; Henbury in Central Australia; Barringer Meteor Crater, Canyon Diablo in Arizona, U.S.A.; Aouelloul in Sahara Occidental; Campo del Cielo in Argentina; the Libyan Desert; Darwin in Tasmania and Macedon in Victoria, Australia.

Those formed in meteorite craters are regarded as "meteorite splashes", and according to Dr. H. B. Stenzel (see Barnes, 1940a, p. 558), should be given the distinctive name "impactites", since they result from the melting of sandstone or desert sand by intense heat generated on impact of a large mass of meteoritic iron.

Natural glass formed electrically from the fusion of sands by the earthing of lightning discharges, is known as *fulguritic glass*.

GLASS FORMED BY METEORITES.

Köfelsite.

Described by F. E. Suess (1936) as blocks and "pumice" scattered around a rock basin near Köfels in the Oetzthal, Tyrol, and probably relics of a meteorite crater 3 to 4 kilometres across. Associated vesicular glassy material enclosing glass fragments, is gneiss fused by the fall of a large meteorite. This fused material ("meteorschmelz"), called köfelsite, is placed as Interglacial (Pleistocene) in age. The pumiceous material, examined spectrographically by Heide (1938), contains 0·001 per cent. nickel, an amount regarded as insufficient to prove Suess' meteorite crater theory of origin for köfelsite. Heide found the average content of nickel in igneous rocks was 0·01 per cent., and the same concentration of nickel as in the Köfels Glass, occurs in glass from volcanic tuffs at Nördlinger Reiss, Germany.

Wabar Glass.

The silica glass from Wabar was found by Philby (1932, p. 932 and 1933) on the site of the ancient city of Al Hadida (Wabar) in Rub al Khali, Arabia, around two shallow meteorite craters. The glass consists mainly of individual "bombs" with a white cellular interior and a black "pimply" surface. The white glass is welded into grey glass with remnants of partially enclosed sintered sandstone. Some of the quartz in these portions is much shattered. The pieces of glass range from the size of a man's head to that of "black pearls" present in considerable numbers. It is thought they developed from a rain of molten silica full of bubbles, that was shot out through vapours of iron and silica, during the explosion of the meteorite (or meteorites) that formed the Wabar craters. Spencer (1937a) drew a parallel between terrestrial meteorite craters and lunar craters, and thought that in the terrestrial desert sands affected by meteorites, the

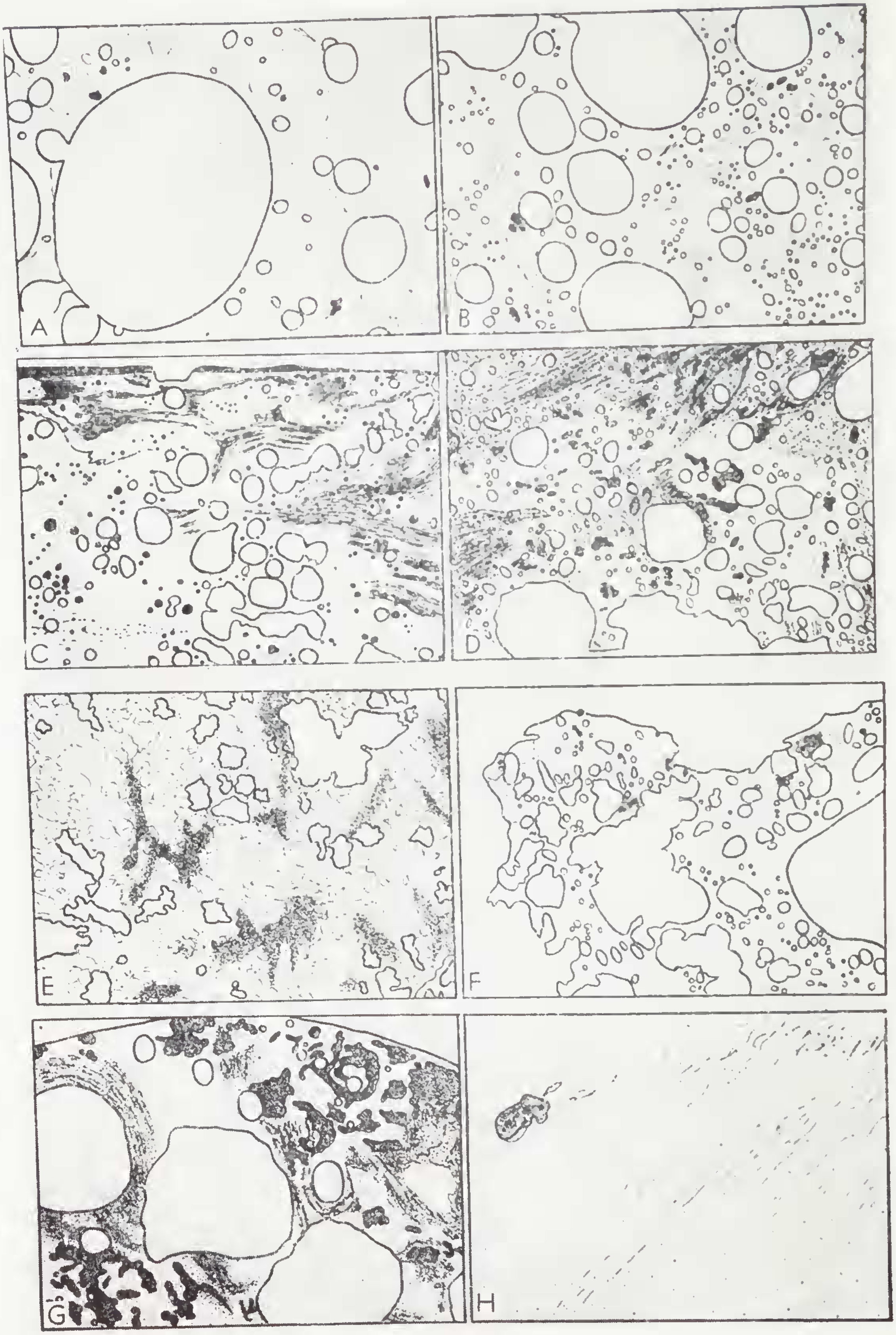

FIGURE 40.

FIGURE 40.—Sketch diagrams showing the internal character of silica glasses.

A—Darwin Glass, Tasmania.
B—Macedon Glass, Victoria.
C—Wabar Glass, Arabia.
D—Henbury Glass, Central Australia.
E—Meteor Crater Glass, Arizona, U.S.A.
F—Fulgurite Glass, Macquarie Harbour, New South Wales.
G—Artificial Glass, from fusion of sandy clay from Port Campbell, Victoria.
H—Libyan Desert Glass, North Africa.

(After Baker and Gaskin, 1946.)

sand not only melted to yield silica glass, but boiled (B.P. = about 3,500°C.) and vapourized. Minute metallic spheres in the Wabar crater glass (fig. 40C) are the same in composition as the meteorite that caused boiling of the desert sands, and occur in numbers up to 2 million per cubic centimetre.

Enormous energy is released when meteorites explode on reaching the earth, as evidenced by the generation of the high temperatures required to melt, boil and vapourize siliceous sands. A. C. Gifford* calculated the energy of a meteorite as 123,900 calories/gram at a velocity of 20 miles a second, and 494,700 calories/gram at 40 miles a second. This value was contrasted with the considerably less energy developed by the explosion of dynamite (1,100 calories/gram).

Henbury Glass.

Natural glass from the Henbury meteorite craters, Central Australia, occurs as small " bombs " made up of an outer rim of dense glass and a cellular interior. It is mainly dark brown to light greenish-brown, although parts are colourless in thin section. It is generally isotropic, with occasional birefringent areas of non-fused quartz remnants and sometimes tridymite. Coloured areas in thin sections are streaky in parts and contain a few lechatelierite particles of irregular, hooked and twisted shapes. The glass is as vesicular (fig. 40D) as some pieces of Darwin Glass and Macedon Glass. Gas pores are principally rounded in outline, a few are elongated.

Barringer Meteor Crater Glass.

This glass (fig. 40E) from Canyon Diablo, Coconino County, Arizona, U.S.A., is one of the most cellular natural silica glasses, being honeycombed with rounded and irregularly-shaped pores. It consists of colourless lechatelierite glass†, and is mostly isotropic.

Some thin sections of the glass show smoke-brown coloured regions with weak birefringence. Pinkish coloured particles resembling the lechatelierite particles observed in other natural silica glasses, have been recorded by Rogers.‡

Residual quartz and cristobalite in the Barringer Meteor Crater Glass, indicate a temperature of formation of from 1,400°C. to 1,800°C. (Rogers, 1930, loc. cit.).

Aouelloul Glass.

The natural silica glass from Aouelloul, Adrar, Sahara Occidental (Campbell Smith and Hey, 1952), is thought to be of meteoritic impact origin on the insecure basis of resemblance to Darwin Glass, Tasmania. The Darwin Glass (q.v.) was first thought to be tektitic, then " impactitic ", but the writer believes that neither origin applies to the Darwin Glass, hence the meteorite impact theory cannot safely be applied to the Aouelloul Glass merely on the grounds of its similarity to Darwin Glass. More convincing, however, is the occurrence of the Aouelloul Glass both within and just outside the crater, thought by Professor Th. Monod

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* " The Mountains of the Moon ", New Zealand Journal of Science and Technology, vol. 7, pp. 129-142 (1924).

† A. F. Rogers, 1930.—" A Unique Occurrence of Lechatelierite or Silica Glass ". American Journal of Science, series 5, vol. 19, pp. 195-202.

‡ A. F. Rogers, 1928.—" Natural History of the Silica Minerals ". American Mineralogist, 13, pp. 73-92.

(1951) to be due to the explosion of a great meteorite on impact, although no meteorite has yet been found (Campbell Smith and Hey, 1952, p. 773). The chemical analysis of the Aouelloul Glass reveals a small but significant amount of nickel (Table 23, column X).

GLASS OF UNCERTAIN ORIGIN.

Libyan Desert Glass.

Pieces of natural silica glass found by Mr. P. Clayton in the heart of the Libyan Desert, are referred to as "cosmic gems" (Spencer, 1933d, p. 111). It was stated in the Queensland Government Mining Journal (vol. XXXV, 1934). that experts considered nothing like this glass had previously been found, but that it somewhat resembled Darwin Glass and Indo-China tektites. The deposits of glass were said to "shine in the desert like an opaque lake". Commenting upon this occurrence, Richards (1934, p. 222) considered that if there was a general resemblance between Libyan Glass, Darwin Glass and Indo-China tektites, then the probabilities are that the source was extraterrestrial. However, it is shown later that Darwin Glass is not necessarily of extraterrestrial origin. Moreover, Spencer (1939, p. 432) noted that Libyan Glass from 500 miles south-west of Cairo, differed in many respects from tektites proper, and its origin presented a difficult problem. This problem has not yet been solved. The chemical composition and general physical characteristics vary considerably from all known true tektites and also from Darwin Glass. Inasmuch as the Libyan Glass characteristically has a very high silica content (98 per cent.), and is a clear, compact glass with but few bubbles or inclusions, it would appear that its origin could lie in the highly siliceous sands in which it is found. The source of heat necessary to rapidly fuse such sands, in the absence of the possibility of all heat sources except lightning phenomena, suggests to the writer that there is a distinct probability of Libyan Glass originating from a fusion of desert sands by lightning on earthing. Admittedly the lumps of Libyan Glass have nothing in common with the shapes of the lightning tubes found in the same area, but inasmuch as the lightning tubes probably result from the earthing of fork lightning, and such tubes are common where the Libyan Glass has been found, it seems likely that lumps of glass could be formed by the earthing of ball lightning. Ball lightning is no longer a figment of the imagination, and it is thought to have been responsible for the fusion of surface sandy soils into clinker-like masses at Mt. Remarkable in South Australia and Tempe Downs in Central Australia (Baker, 1953). These are in regions where all other sources of heat of sufficiently high temperatures have been shown to be absent, but are on hilltops where lightning would be expected to earth. Being fused soils, the resultant clinkers are by no means as siliceous as Libyan Glass, but like it, they occur as irregularly shaped lumps, a fact which in itself, militates against an origin similar to that which shaped the tektites. Moreover, these clinkers are not completely fused, inasmuch as they consist of quartz grains embedded in a matrix of glass, and most pieces have a distinctly vesicular to scoriaceous character. Libyan Glass, on the other hand, is dense and compact. However, it is to be expected that different materials on different parts of the earth's surface, would, if the opportunity arose, be fused into somewhat different products. One of the differences between the Tempe Downs sinter and the Mt. Remarkable sinter, lies in the ratios of fused to unfused material in each, as revealed by microscope sections. The proportion of glass to unfused quartz is 25 : 75 for the Tempe Downs sinter, and 70 : 30 for the Mt. Remarkable sinter, thus showing that different degrees of fusion of natural materials has

occurred by natural heating. This suggests that the Libyan Glass, if formed under like conditions, must have been generated at higher temperatures of fusion from purer ingredients.

Spencer found no Libyan Glass in the Cairo Museum of Antiquities, among the variety of ornamental stones used by the Egyptians, but Oakley (1952, p. 447) has recently described artefacts made of Libyan Glass as probably being Alerian and hence having an antiquity of some 10,000 to 20,000 years. The largest piece of Libyan Glass found during Spencer's expedition (1934) weighed 13¼ lbs. Lumps and broken pieces of the glass were irregular in shape, ranging in weight from a few grams to 7¼ kilograms. The glass is mostly much pitted with deep conical pits and tubular cavities, and has been worn by sand-blasting. Its colour is pale yellowish-green, and the glass is clear to cloudy due to minute gas bubbles and dust, and sometimes shows parallel bands and brown flow streaks in paler coloured pieces (fig. 40 H). Some pieces contain white spherulitic cristobalite up to 1 mm. in size.

Spectrographic analyses by Professor A. Fowler, Professor V. M. Goldschmidt, Mr. Ramage, Mr. F. E. Chapman and Dr. E. Preuss, reveal Mg, Fe, Ca, Sr, Mn, Ag, Li, Na, K, Pb, Ni, Ga, Cu, Al, Ba, Si, Zn, Ti, Cd and Cr. Spencer thought there was no connection between the lumps of Libyan Glass and fulgurites found nearby, and there are no indications of associated meteorites or meteorite craters. He suggested that the Libyan Glass might have had a celestial source, but that its origin and manner of arrival in the Libyan Desert are still wrapped in mystery. It has also been suggested that glasses formed on some celestial body which was destroyed by collision, would have a wide range in composition, and could include supposedly non-tektitic glasses such as Libyan Desert Glass.

Darwin Glass (*Queenstownite*).

This natural glass,* first found at Ten-mile Hill and later near Crotty, and 5 miles south-west of Mt. Sorell and also east of Mt. Darwin in the Jukes–Darwin mining field, Tasmania (fig. 5), occurs loose on the surface and in the upper nine inches of superficial deposits (Loftus Hills, 1915, p. 4). It consists of slaggy and stalactitic pieces of silica glass (Plate XXIII, fig. A), but very seldom shows regular shapes. One or two pieces shaped like pear-drops and discs have been observed. They range in size from rounded drop-like masses the size of a pin's head, to irregular fragments 6 cms. long by 2·3 cms. wide and weighing 21 grams (Loftus Hills, 1915, p. 8).

The term *Queenstownite*, proposed by F. E. Suess (1914) for Darwin Glass, is seldom used nowadays. The glass was originally described by Suess (1914) who quoted its mode of occurrence from a detailed letter sent by Loftus Hills and Twelvetrees. Suess regarded the Queenstownite as slag-like cakes of glass deformed by softening during fall through the atmosphere. It has been referred to by local inhabitants as " petrified kelp " and classified with the tektites by Loftus Hills (1915, p. 14).

European authorities in certain quarters, expressed the opinion that Queenstownite resembled ragged slags that had spread out when molten, and might be remnants of an ancient cultural era (Berwerth, 1917). Accordingly, it was thought that the varying shapes and compositions made it possible for them to be by-products of some smelting process, as they compared with average (Bunter) sandstones, on analysis, and this so-called variety of the tektites could thus

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* For detailed map of distribution, see David, Summers and Ampt (1927).

represent a mechanically mixed, fused accidental product. Berwerth expected the solution of the problem of the origin of the Queenstownite to come from archaeologists, but stressed the significance of the presence of copper furnaces near sites of discovery, and he thought the glass might alternatively have been due to the throwing of sand into fires, thus forming a true slag. Loftus Hills (1915, pp. 3 and 13), pointed out that at Mt. Darwin, the glass could not have had an artificial or a volcanic origin.

Darwin Glass has also been compared with fulgurites from Griqualand, South-west Africa, and its high silica content (89·81 per cent.) considered as separating it from volcanic glass but not from fulgurites, which sometimes had even more silica (Dunn, 1916, p.227). At the same time, it was believed that the peculiar ropy structure of Darwin Glass and the highly glazed channels traversing some fragments, greatly resembled these features on certain fulgurites. The conclusion was that Gregory's (1912, p. 36) suggestion of glassy australites owing their origin to lightning, was quite applicable to Darwin Glass. A fulguritic origin, however, has been regarded as incapable of accounting for the plentiful distribution of the glass, and also incapable of accounting for the chemical composition of analysed pieces (Loftus Hills, 1915, p. 13). The probability of Darwin Glass being artificial, volcanic or fulguritic, has been discounted by David, Summers and Ampt (1927), who described the glass as being largely fragmentary, with some spirally twisted, stalactitic forms (Plate XXIII, fig. A) and rare teardrop and disc-like pieces. The density of the powdered glass was determined as 2·28 to 2·29, the hardness as just below 7, and the colour as variable from dark smoky-green to almost black, but translucent in thin fragments. Some pieces of the Darwin Glass are grey, others olive-green, yellowish-green, greyish-green and at times almost white from extreme vesicularity. Darwin Glass is transparent in thin sections, isotropic, and the lustre vitreous to dull. A few pieces are said to contain minute black specks. Most pieces have flow lines, and the majority show numerous, small, round and rare elongated vesicles under the microscope, some possessing many more than others, and being highly vesicular in parts. The refractive index of the glass is 1·486 to 1·497, and the specific refractivity 0·2065 to 0·2088.

Tests for radioactivity by different authors have yielded variable results. Earlier tests were negative, but Dubey (1933) obtained a value of $0 \cdot 50 \times 10^{-12}$ Ra per gram from Darwin Glass, as compared with $0 \cdot 96$ and $0 \cdot 85 \times 10^{-12}$ Ra per gram for australites. W. G. Fenner (see C. Fenner, 1949, p. 15) obtained similar beta counts for Darwin Glass (11 counts per minute) as for australites (11·5 mean count per minute), and it was concluded that there appeared to be radioactive similarity between Darwin Glass, australites, indochinites and rizalites. On the other hand, tests for radioactivity of fulgurites have so far proved negative.

Darwin Glass was originally correlated with schonite, billitonites, moldavites and australites, and considered to show close relationships in composition to tektites (cf. David, Summers and Ampt, 1927, p. 179; Loftus Hills, 1915, p. 12). Such relationships have been indicated by variation diagram comparisons of molecular ratio percentages, and significance was attached to the location of Darwin Glass on the same great circle in common with certain tektites (see fig. 29). On these grounds, it was thought to be probable that all these glasses belonged to one and the same group of meteorites, having been either discrete swarms of small meteorites, or the scorification products of separate larger bodies. Darwin Glass was also later referred to as an aberrant type of the tektites (Lacroix, 1932).

Later, it was thought that a tektitic origin did not fit in with several aspects of Darwin Glass and its mode of occurrence, and so its origin on the basis of the meteorite splash hypothesis, advocated by Spencer (1933) for certain tektites, has been supported by several writers. Darwin Glass was compared with the meteorite crater glass from Wabar in Arabia and Henbury in Central Australia (Conder, 1934), and suggested as being formed by the fall of a large meteorite that fused sediments at the point of impact. Absence of meteorite craters and meteorites was suggested as due to rapid destruction caused by severe denudation in the West Coast regions of Tasmania, where the Darwin Glass occurs in a relatively restricted area. Conder also favoured a meteoritic splash mode of origin because of the claim that strings of magnetic spheres occurred in the glass, just as in the Wabar meteorite crater glass. The writer has been unable to locate such strings of magnetic bodies in polished surfaces of the Darwin Glass, while Campbell Smith and Hey (1952, p. 773) likewise found no such bodies in examples examined recently. What does appear, and could possibly be mistaken for such opaque bodies, are small bubble holes infilled with fine grinding powder during the preparation of thin sections of the Darwin Glass. Alternatively, if magnetic spheres do occur in some pieces of the glass, they could readily be comparable with the small bodies of magnetite determined by polished surface examination of the Mt. Remarkable natural sinter from South Australia (Baker, 1953) or, where non-magnetic, comparable with the minute globules of pyrite determined from polished surfaces of the Tempe Downs natural sinter from Central Australia, both of which sinters, with their partial cements of secondarily fused glass, are undoubtedly terrestrial products developed by high temperature, but not prolonged terrestrial means of heating.

Further to the suggested meteoritic splash mode of origin of Darwin Glass, Conder (1934) found it difficult to accept previous ideas that the slag-like Darwin Glass descended as a sort of meteoritic hailstorm or as a large mass that exploded on reaching the earth. Thousands of tons of the glass were originally estimated to occur over an area 10 miles long and 6 miles wide. Other estimates reduce this estimate to hundreds of tons (David, 1927). There would have to be a meteoritic fall of extraordinarily large dimensions or numbers to yield such a large quantity of glass. It is perhaps worthy of note that the writer has been unable to verify the statement that such a large quantity of Darwin Glass was known to occur in the field, and it is indeed difficult to obtain even a few specimens for study from any source nowadays, as also experienced by Fenner (1940, p. 318).

Beyer (1934), F. E. Suess (1936), Michel (1939), Spencer (1939, p. 432) and La Paz (1944, p. 140) also agreed to the inclusion of Darwin Glass with the group of silica glasses formed in meteorite craters. Spencer (1939, p. 432) thought the vesicular and slaggy pieces had much the same appearance and chemical composition as the abundant silica glass from meteoritic craters at Wabar, Arabia, and that the small clear fragments (which are more rare than the slaggy pieces) closely resembled silica glass from the Libyan Desert. He had suggested earlier (1937) that as no trace of meteoritic iron or meteorite craters were found where Darwin Glass was located, the silica glass was all that was left to tell the tale, because silica glass is very resistant to chemical erosion, has a low coefficient of thermal expansion, and is therefore not readily broken up by changes of temperature.

Campbell Smith and Hey (1952, p. 773) also consider that Darwin Glass bears some resemblance to Wabar Glass, but that the resemblance to Aouelloul Glass is even more striking.

Fenner (1940, p. 318) remarked that the striking features about specimens of Darwin Glass are their "frothiness," their "slightness," and the numerous bubbles showing internal "hot polish" common to silica glass bubbles. He found no "perfect forms" like those of australites, except for a minute dumb-bell-shaped piece. (David, Summers and Ampt, 1927, have figured one small pear-shaped piece). Irregular pieces of Darwin Glass, which constitute the greater bulk and number, have been classified by Fenner into ten groups, according to the nature of their outlines and certain marked surface structures. Loftus Hills (1915, p. 9) found no structure or signs of crystallization in thin sections of the glass. The "pimply excrescences" on some pieces of Darwin Glass examined by Loftus Hills, (1915, p. 4), are interesting in that such phenomena are not shown by non-weathered tektites, and are characteristic of terrestrial glasses formed from the fusion of terrestrial materials, by a terrestrial means of heating.

Microsections of the Darwin Glass (fig. 40, A) examined by the writer show many conspicuous flow lines and a few coloured streaks. The flow structures are more prominent when viewed in oblique illuminations, or with a sensitive tint plate inserted in the microscope system. The coloured streaks are of smoky appearance and vary in density from place to place, and are, in fact reminiscent of "smoke" or streaks of carbonaceous matter of extremely fine sized particles, such as can be observed in some natural glasses formed by the slow incineration and ultimate fusion of the ash from organic matter containing some admixed mineral matter (Baker, 1954). Paler coloured bands in the Darwin Glass sometimes show weak strain polarization, and represent more siliceous areas free of organic or other matter that leads to discolouration. The lechatelierite particles in Darwin Glass are not particularly frequent as such, because they have been largely drawn-out into streaks and ribbons along flow directions; a few particles are irregular in shape, some are elongated and twisted, all are residues of re-fused quartz that were not completely absorbed into more homogeneous parts of the glass.

Macedon Glass.

Vesicular silica glass similar in every respect to Darwin Glass has been located at Macedon in Victoria (Baker and Gaskin, 1946, p. 88), some 400 miles to the north of the Darwin Glass occurrence. Only two small pieces of the Macedon Glass are known, one being dark-grey in colour, the other light greenish-grey; both have a sub-vitreous to highly vitreous lustre. The hardness, like that of Darwin Glass, is just under 7, density values (1·935 and 2·080) are comparable with those for Darwin Glass (1·874 to 2·180), and refractive indices are also similar.

Macedon Glass is like Darwin Glass in thin sections (fig. 40, B) but does not contain magnetic, metallic spheres recorded as abundant in Darwin Glass by Spencer (1933e, p. 571). It contains lechatelierite particles like those in Darwin Glass.

ARTIFICIAL GLASS.

Artificial Silica Glass.

The glass prepared by fusing leached sandy clay containing 27·5 per cent. quartz sand, 66·5 per cent. clay constituents and 6 per cent. material soluble in 1 : 1 hydrochloric acid, in an oxidizing oxy-acetylene flame on a carbon boat, is very similar in all characteristics to Darwin Glass and Macedon Glass. It contains rather more conspicuous quantities of lechatelierite particles because

of incomplete fusion (fig. 40, G). The association of numerous very small gas bubbles with the lechatelierite particles, suggests that gas pores formed in the glass during transition of quartz grains to lechatelierite pseudomorphs.

Atom-Bomb Crater Glass. ("Trinitite").

Silica glass has been formed in craters produced by the experimental atom bomb explosions created at Alamogordo in New Mexico, United States of America. Rapid heating at high temperatures, resulted in melting of quartz sand, some of which was volatilized, but in more favourable locations, some was melted and rapidly chilled to form silica glass showing a strain polarization pattern, which is essentially similar to such patterns in natural silica glasses such as the Darwin Glass, Macedon Glass and Aouelloul Glass. The atom-bomb crater glass * also contains crowds of small gas pores in places, and many bubbles of spherical shape that are up to 1 cm. across. Hand specimens of this glass are pale bottle-green, while thin slices are colourless with occasional brownish coloured streaks and a few streaks of glass possessing a rather lower refractive index than neighbouring parts, thus producing flow lines.

Laboratory Silica Glass.

The artificial silica glass prepared for chemical ware, is entirely isotropic, clear and colourless in thin sections. In this well-mixed glass, prepared from selected constituents, there are virtually no streaks, lechatelierite particles or flow lines. This is in contrast to the majority of the natural silica glasses where impurities such as the clay minerals and other alumino-silicates, &c., as well as possibly incompletely volatilized carbonaceous residues in some examples, have added to the compositions.

GLASS FORMED BY LIGHTNING.

Fulgurites†

Reference to lightning tubes is included herein, because some writers have suggested that tektites might have had an electrical mode of origin, in having developed during lightning discharge.

The opinion has been expressed that fulgurite glass, formed by lightning fusing rock, was the purest natural silica glass in the world (Twelvetrees and Petterd, 1897). It was described as structureless, with no crystallization products whatever—only glass enclosures and gas vesicles. Analyses of "sand-tube" fulgurites (Fenner, 1949, p. 134) show a range in silica content from 88·46 per cent. to 96·44 per cent., which falls a little short of the silica-rich (98 per cent. SiO_2) glass from the Libyan Desert.

Over, 2,000 fulgurites have been found in 8 square miles of sand dunes at Witsands, Kalahari, where natives do not recollect violent electrical storms occurring (Lewis, 1936, p. 50). These fulgurites mostly occur as broken fragments, the longest recovered being 8 feet and only 0·2 to 0·5 inches in diameter. They are friable tubes of fused silica, some of which are branching,

* C. S. Ross, American Mineralogist, 1948, 33 pp. 360-362.

† For bibliography, see J. J. Petty, American Journal of Science, 1936, vol. xxxi, pp. 198-201; A. Lacroix, Bull. Serv. Mines Afrique Occid. Franc. Dakar, 1942, no. 6, p. 23 (M.A. 9:104), and A. F. Rogers, Journ. Geol., Chicago, 1946, vol. 52, p. 117 (M.A. 10:340).

some up to two inches across and some have collapsed with the formation of longitudinal ribs. Threads of fused silica stretch across one tube. The sand surrounding the fulgurites was darkened by iron vapourized from the fused portion of the sands. Lewis was reluctant to accept the view that the tubes were formed by lightning discharge, and suggested as an alternative explanation formation from meteorites, which explanation he thought was supported by the finding of lechatelierite (silica glass) in meteorites (an incorrect statement according to the reviewer of Lewis' paper).

Many fulgurites occur in the Libyan Desert (Spencer, 1939). Rutley (1885) described one from Mt. Blanc. Dunn (1916, p. 227) referred to several from Griqualand, Southwest Africa. They also occur at Bondi and very abundantly at Macquarie Harbour, New South Wales (Plate XXIII, fig. B). They are known from Queensland, South Australia, Central Australia and Western Australia (Fenner, 1949, pp. 132-133). In Victoria, they have been found at Red Cliffs, Yarrara, Tempy, Bronzewing and south of Cowangie. There are many occurrences in other parts of the world. The density of fulgurites is approximately 2·2 and the refractive index 1·465.

Lightning tubes in the Libyan Desert are thin-walled with a glazed inside ("lumen"), and have partly fused grains adhering to the outside (Spencer, 1939, p. 437). The longest tube here, measured 6 feet 2 inches. A micro-section showed the fulgurite glass was full of round and elongated bubbles, and was isotropic, containing greyish-brown streaks and clouds. A section of a Macquarie

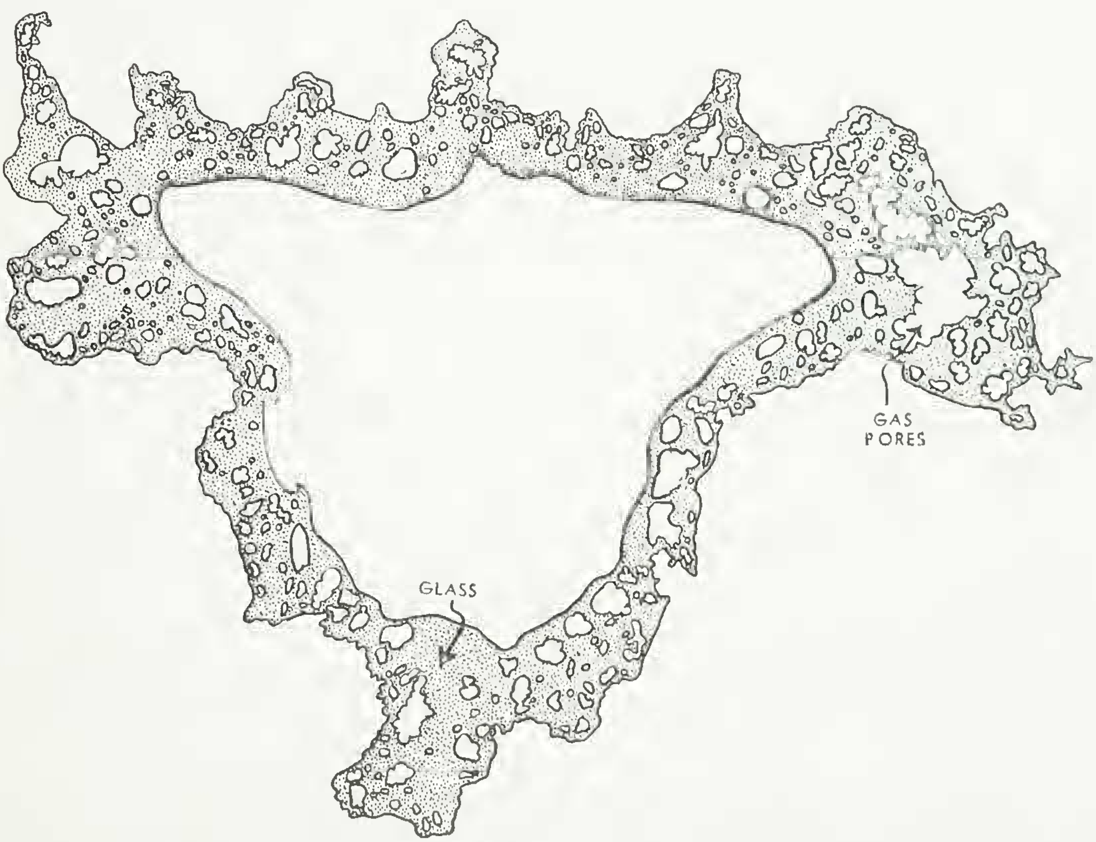

FIGURE 41.—Sketch micro-section of fulgurite, showing smooth internal and rugose external walls of lechatelierite glass tube with numerous gas pores. From Macquarie Harbour, New South Wales (× 10).

Harbour, New South Wales, fulgurite (figs. 40, F and 41) likewise shows principally isotropic and colourless lechatelierite glass, with abundant vesicles. Rare areas near the rugose external surface (fig. 41) show polarization colours. These are uniaxial and represent residues of incompletely fused quartz; biaxial portions, which are also rare, represent tridymite.

Rare streaks and patches of smoky-grey to brown glass are evidently portions richer in iron oxide or other such impurities. Similar streaks occur in a fulgurite from Poland (Julien, 1901). Flow lines are inconspicuous in fulgurite glass, but some flowage is indicated by the occasional alignment of small gas pores around larger cavities. Glass pinnacles projecting into some bubble cavities are remnants of the walls of earlier-formed bubbles that coalesced to form larger, less regular cavities. Such structures seldom appear in other natural silica glasses, although the glass pinnacles are somewhat allied to the septum separating the two internal cavities of the australite with a double bubble, shown in Plate XIV, fig. 2, although on a much smaller scale. Lechatelierite particles are particularly rare in fulgurite glass, because the glass itself is almost entirely lechatelierite. A few particles discerned in some specimens are nodular in shape, isotropic, and have lower refractive index than the enclosing glass.

The evidence of the fulgurites has been regarded as distinctly in opposition to the theory of a fulguritic (electrical) origin for tektites (Fenner, 1949, p. 139), a conclusion with which the majority of tektitological students would agree.

COMPARISONS BETWEEN THE GLASSES.

Considerable variations occur between the several types of natural silica glasses. The bubble content varies from piece to piece even among natural silica glasses of the same kind from the same locality, while there are also marked differences in the complexity of flow line patterns, the number and nature of lechatelierite particles, and the colour of these natural silica glasses. They range from the normally very vesicular Darwin Glass and Macedon Glass, to clear, least vesicular glass from Libya that closely resembles the laboratory silica glass prepared for chemical-ware, both in purity and in appearance generally in thin section.

The type of silica glass formed at any one place on the earth's surface, depends primarily on the original unfused material, and secondarily on the temperature and duration of fusion and cooling, irrespective of the means of fusion. Glasses with few or no lechatelierite particles, a small proportion of streaks and bands and few bubbles, formed at either higher or more prolonged temperatures, because most irregularities in them have been smoothed out. The greater vesicularity and slag-like appearance of natural silica glasses from Darwin, Macedon, Henbury, Wabar, Aouelloul, and Barringer Meteor Crater, place them in a class apart from tektites proper.

The silica contents, densities, refractive indices (n) and specific refractivities (k) of some of the natural silica glasses are compared in Table 22.

TABLE 22.

Silica Glass Relationships (from Spencer, 1939, *with more recent additions).*

Type of Glass and Locality.	SiO_2.	Density.	n.	k.
	%			
Mt. Remarkable, Port Pirie, S.A.* (glass matrix in sinter)	63·54	2·57	1·535	0·2081
Black Glass, Henbury, C.A.	68·88	2·31	1·545	0·2359
Tempe Downs, C.A.* (glass matrix in sinter) ..	76·08	2·54	1·530	0·2087
Darwin Glass, Mt. Darwin, Tas.	86·34	2·296	1·474	0·2065
Aouelloul Glass, Sahara Occidental‡	86·92	2·285	1·488	0·2136
Black Glass, Wabar, Arabia	87·45	2·24	1·500	0·2232
Dark-grey Glass, Macedon, Vic.†	—	2·08	1·490	0·2356
Greenish-grey Glass, Macedon, Vic.†	—	1·940	1·485	0·2500
Darwin Glass, Mt. Darwin, Tas.	88·76	2·2921	1·479	0·2088
Darwin Glass, Mt. Darwin, Tas.	89·81	2·2845	1·477	0·2087
Darwin Glass, Mt. Darwin, Tas.	—	2·275	1·479	0·2105
White Glass, Wabar, Arabia	92·88	2·10	1·468	0·2229
Fulgurites, Australia	96·44	2·20	1·465	0·2114
Silica Glass, Libyan Desert	97·58	2·206	1·4624	0·2094
Lechatelierite, Barringer Meteor Crater, Arizona, U.S.A.	98·63	2·10	1·460	0·2190
Pure Silica Glass (artificial)	100·00	2·203	1·4585	0·2081

* From G. Baker, "Natural Sinters from Mt. Remarkable and Tempe Downs," Trans. Roy. Soc. S. Aust., 76, 1953.

† From G. Baker and A. J. Gaskin, "Natural Glass from Macedon, Victoria, and its Relationships to Other Natural Glasses," Journ. Geol., LIV, 1946.

‡ From W. Campbell Smith and M. H. Hey, "The Silica-glass from the crater of Aouelloul (Adrar, western Sahara)," Bull. Inst. franc d'Afrique noire, XIV, 1952.

Spencer (1939, pp. 430-431) showed on graphs that the data for these silica glasses did not accord at all well with the true tektite series, and that there was a general decrease in density, refractive index and specific refractivity as silica increases.

Available analyses showing the chemical compositions of natural silica glasses from various parts of the world, are compared in Table 23. Two hitherto unpublished analyses (partial) of australites, one analysis of obsidian, one of tachylyte, two of straw silica glass, one of slag from charcoal and one fulgurite glass, are included for purposes of comparison.

TABLE 23.

Chemical Analyses of Natural Silica Glasses, etc.

	I.	II.	III.	IV.	V.	VI.	VII.
	%	%	%	%	%	%	%
SiO_2	92·88	87·45	68·88	86·34	87·00	88·76	89·81
Al_2O_3 ..	2·64	1·77	5·60	7·82	8·00	6·13	6·21
Fe_2O_3	0·23	0·28	8·46	0·63	0·19	—	0·26
FeO	0·53	5·77	7·92	2·08	1·93	1·24	0·90
MnO	0·01	0·01	0·05	nil	nil	tr.	tr.
MgO	0·47	0·60	2·03	0·92	0·82	0·58	0·73
CaO	1·46	1·90	2·51	0·05	nil	0·17	—
Na_2O ..	0·42	0·39	0·03	0·15	0·14	0·13	0·01
K_2O	1·61	0·58	1·43	0·87	0·99	1·36	1·05
H_2O	0·43	0·12	0·08	0·46	0·36		—
CO_2	nil	—		nil	nil	—	—
TiO_2	0·12	0·15	3·64	0·52	0·51	1·24	0·86
P_2O_5	tr.	tr.	nil	tr.	nil	—	—
ZrO_2 ..	nil	—		0·11	tr.	—	
Cr_2O_3 ..	nil	—		nil	nil	—	—
NiO	nil	0·35	0·28	nil	nil	—	—
CoO	nil	tr.	tr.	nil	nil	—	—
CuO	nil	nil	tr.		—	—	—
BaO	nil		—	nil	nil	—	—
SrO	0·01	0·01	nil	nil	nil	—	—
SO_3	nil	—	—	nil	nil	—	—
Cl	nil		—	nil (?)	nil (?)	—	—
S	nil	—	—	—	—	—	—
Total ..	100·81	99·38	100·91	99·95	99·94	99·61	99·83

TABLE 23—*continued.*

	VIII.	IX.	X.	XI.	XII.	XIII.	XIV.
	%	%	%	%	%	%	%
SiO_2	98·20	86·92	86·10	71·70	70·22	70·61	50·87
Al_2O_3 ..	0·70	6·47	5·05	13·90	13·96	8·59	14·33
Fe_2O_3	0·53	1·16	1·45	6·70	6·58	2·52	5·37
FeO	0·24	1·72	1·45			5·96	7·25
MnO	—	0·04	0·05	0·02	0·02	0·34	0·58
MgO	0·01	0·32	1·50	2·70	2·71	0·07	4·51
CaO	0·30	0·55	0·90	5·25	4·65	0·61	8·22
Na_2O ..	0·33	0·23	0·05	n.d.	n.d.	6·77	3·39
K_2O	0·02	2·05	2·05	n.d.	n.d.	4·46	1·35
H_2O	0·06	0·29	0·40	—	—	—	0·50
CO_2	—	nil	nil		—	—	0·03
TiO_2	0·23	0·49	0·60	tr.	tr.	0·15	3·38
P_2O_5	—	n.d.	0·06	—	—	—	0·07
ZrO_2	—			—	—	—	—
Cr_2O_3 ..	—	—	—	—	—	—	—
NiO	0·02	0·019	0·025	—	—	—	0·06
CoO	—	nil	n.d.	—	—	—	—
CuO	—	—	—	—	—	—	—
BaO	—	—	—	—	—	—	—
SrO	—	—	—	—	—	—	—
SO_3	—	—	—	—	—	—	—
Cl	—	—	—	—	—	—	—
S	—	—	—	—	—	—	—
Total ..	100·64	100·26	99·68	100·27	98·14	100·08	99·91

TABLE 23—*continued.*

	XV.	XVI.	XVII.	XVIII.	XIX.	XX.
	%	%	%	%	%	%
SiO_2	66·04	57·40	81·03	88·46	63·54	76·08
Al_2O_3	1·55	1·81	2·99	6·69	18·59	10·27
Fe_2O_3	0·59	0·59	0·58	1·16	1·56	1·67
FeO	—	—	0·78	—	3·48	2·59
MnO	—	—	tr.	tr.	0·18	0·08
MgO	3·80	5·56	1·15	0·17	1·50	1·83
CaO	6·00	8·56	8·21	0·17	5·94	3·05
Na_2O	6·88	8·98	2·34	0·01	0·61	0·77
K_2O	11·98	13·58	2·07	2·68	2·20	2·34
H_2O	—	—	0·24	—	0·20	0·26
CO_2	—	—	tr.	—	nil	nil
TiO_2	—	—	0·34	0·46	0·61	0·78
P_2O_5	—	—	0·24	—	1·61	0·31
ZrO_2	—	—	—	—	—	—
Cr_2O_3	—	—	—	—	nil	nil
NiO	—	—	—	—	nil	nil
CoO	—	—	—	—	—	—
CuO	—	—	—	—	—	—
BaO	—	—	—	—	—	—
SrO	—	—	—	—	—	—
SO_3	—	—	nil	—	nil	nil
Cl	—	—	tr.	—	nil	nil
S	—	—	—	—	—	—
Total	99·53*	99·64†	99·97	99·80	100·02	100·03

* plus 2·69 carbonaceous matter.

† plus 3·16 carbonaceous matter.

KEY TO TABLE 23.

I. Silica Glass (White variety), Wabar, Arabia. (anal. M. H. Hey).

II. Silica Glass (Black variety), Wabar, Arabia. (anal. M. H. Hey).

III. Silica Glass (Black), Henbury, Central Australia. (anal. M. H. Hey).

IV. Darwin Glass (Smoke-grey), Darwin, Tasmania. (anal. G. A. Ampt).

V. Darwin Glass (Pale greenish-grey), Darwin, Tasmania. (anal. G. A. Ampt).

VI. Darwin Glass (Olive-green), Darwin, Tasmania. (anal. E. Ludwig).

VII. Darwin Glass (Dirty white), Darwin, Tasmania. (anal. E. Ludwig).

VIII. Silica Glass (Greenish-yellow), Libyan Desert. (anal. M. H. Hey).

IX. Silica Glass (Olive-green to iron-grey), Aouelloul, Adrar, Sahara Occidental. (anal. D. I. Bothwell).

X. Silica Glass (Olive-green to iron-grey), Aouelloul, Adrar, Sahara Occidental. (anal. Centre Technique d'analyse chimique, Paris).

XI. Australite glass (flange), Mulka, Lake Eyre District, South Australia. (anal. A. B. Edwards).

XII. Australite glass (body portion of XI), Mulka, Lake Eyre District, South Australia. (anal A. B. Edwards).

KEY TO TABLE 23—*continued.*

XIII. Obsidian, British East Africa. (anal. G. T. Prior).

XIV. Tachylyte, Meredith, Victoria. (anal. A. G. Hall, Rec. Geol. Surv. Vic., III, 3, p. 324, 1914).

XV. Straw Silica Glass, O. B. Flat, South Australia. (anal. F. L. Dalwood).

XVI. Straw Silica Glass, Compton Downs, South Australia. (anal. F. L. Dalwood).

XVII. Slag formed from charcoal (boxwood) in the suction gas plant, Stawell, Victoria. (anal. F. F. Field).

XVIII. Fulgurite Glass, West Popanyinning, Western Australia. (anal. E. S. Simpson).

XIX. Natural Sinter with glassy matrix, Mt. Remarkable, near Port Pirie, South Australia. (anal. G. C. Carlos).

XX. Natural Sinter with glassy matrix, Tempe Downs stock station, Central Australia. (anal. G. C. Carlos).

Table 23 shows Libyan Glass is the most acidic, Henbury Glass the most basic of natural silica glasses. Most are more acidic than australites and obsidian, and all have far higher silica content than tachylyte. Slag from boxwood (Table 23, column XVII) has a silica percentage between that of australites and silica glass generally, but its alumina content is much lower than all except Wabar Glass. The natural sinters from Mt. Remarkable and Tempe Downs, contain the highest alumina contents of the series set out in Table 23, one containing even more than tachylyte (Table 23, column XIV), but the sinters are types with variable proportions of glassy matrix that could not be isolated for separate chemical analysis.

Darwin Glass is richer in alumina and magnesia, poorer in iron and lime than most other silica glasses. Its range in iron content is a reflection of colour variability in different pieces. Although the analyses of Darwin Glass set out in Table 23 (see columns IV to VII) show no NiO, Heide and Preuss both found 0·04 per cent NiO, an amount somewhat comparable with the NiO content of the Libyan and Aouelloul glasses. Nickel has also been shown present in Darwin Glass by spectrographic means (Baker and Gaskin, 1946), in amounts similar to that in Macedon Glass, artificially fused sediments, australites, Pelée's Hair, tachylyte, &c., so that little certainty attaches to any mode of origin suggested for Darwin Glass based on nickel content.

Compositional variations as between the natural silica glasses, excluding tektites and terrestrial volcanic glass, result from the fusion of different original materials, and their trace-element contents depend primarily upon the composition of the source material and secondarily on the extent of original trace-element removal (or possibly addition) during the process of fusion. The fulgurite glass (Table 23, column XVIII) has relatively high potash and alumina contents due to the felspathic nature of the parent sands in the West Popanyinning district, W.A.

COMMENTS ON ORIGIN OF NATURAL SILICA GLASSES.

The origin of some of the known natural silica glasses is well established, but considerable doubt exists about others. Glasses from Henbury, Wabar and Barringer Meteor Crater, Arizona, are definitely products of fusion from

meteoritic impact, being found associated with meteorite craters, iron shale and metallic meteorites. Köfelsite from Tyrol most probably falls into the same category.

Fulgurite glass forms from the instantaneous fusion of sands when lightning earths in them (Julien, 1901), and is thus of electrical origin. The natural sinters from Mt. Remarkable and Tempe Downs in Australia, seem best explicable in terms of fusion of sandy soils by ball lightning.

The origin of the Libyan, Aouelloul, Darwin and Macedon glasses is still uncertain, because no conclusive associated evidence has yet been found. Hypotheses relating to the origin of Libyan and Darwin glasses are conflicting, and as equally open to criticism as the various theories advanced as explanations of the source of less pure silica glasses classified as normal tektites. The suggested origin of the Aouelloul Glass is partly founded upon the insecure basis of its likeness to Darwin Glass.

Since tektitic, meteoritic, electrical, volcanic and artificial modes of origin as advanced to explain Darwin Glass, fail to supply any convincing proof of any particular method of its formation, recourse has to be made to a combination of circumstances that point to the probability of a partially vegetable—partially mineral parentage and fusion by means of natural fire. It would initially appear that the irregularly-shaped bodies constituting Darwin Glass might not be expected to develop from the burning of vegetation purely and simply, because they differ so widely in chemical composition from glassy products of that nature (see Table 23, column XV). It is possible, however, that Darwin Glass could have formed in burning peat horizons, given the right conditions, the right kind of vegetation, and a certain amount of fine silica and clay minerals associated with the peat. Peat bogs in certain parts of Tasmania do catch fire and slowly burn for a long period, but there is no record of glass having been searched for or collected from the sites after recent fires. The chances of older peat bogs catching fire could be greater, for certain periods of Quaternary history were much drier than now, so that peat horizons already present at the onset of drier periods, might well be favourably situated for spontaneous ignition, as observed, for example, at Leigh Creek in South Australia*, where the characteristic liability of sub-bituminous coal to combustion in a sub-arid region, under favourable circumstances, resulted in the generation of a basic clinker, on fusion by natural fire of coal ash produced on the incineration of the constituents of the coal. The Darwin Glass was formerly considered to have fallen about the time of Pleistocene glaciation in Western Tasmania (David, Summers and Ampt, 1927), but if formed in the manner suggested herein, the incineration of peaty material and fusion of the contained siliceous, &c. material, would have to occur in a pre-glacial period towards the close of the Pliocene or early in the Pleistocene.

It is known that many of the present day swampy areas containing peat in the West Coast region of Tasmania, support abundant growths of "button-grass" (*Gymnoschoenus sphaerocephalus*), a plant relatively rich in SiO_2 (see Baker and Gaskin, 1946, p. 101). The peat also contains a certain amount of siliceous and clayey matter, as finely divided, transported quartz, &c. No doubt, similar types of grass flourished in early Quaternary times. In view of the presence of fluxes in the peat, sufficiently high temperatures could have been generated in smouldering peat horizons, to fuse the contained mineral matter

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* G. Baker, "Naturally Fused Coal Ash from Leigh Creek, South Australia". Trans. Roy. Soc. S. Aust. 76, 1953.

and any silica added from silica-containing plants. Even though the glass as now found has to be heated to 1,450°C. before it melts, it is not so improbable that the original ingredients fused more readily at lower temperatures, in the presence of fluxes, and that most of such fluxes were subsequently volatilized during slow, prolonged burning. After all, it is known that a piece of " straw silica glass " the size of a man's fist, is often left behind after the rather more rapid incineration of a hayrick. Then again, it is apparent that at Leigh Creek in South Australia, the exothermic nature of the process that led to combustion of sub-bituminous coal and ultimately fusion of parts in favourable situations, resulted in the generation of temperatures of at least 1,300°C., to account for the newly formed mineral assemblage on slow crystallization. It is but a step further to contemplate that a slowly burning peat horizon at shallow depth and possessing the requisite ingredients, could well give rise to a glass of the character of Darwin Glass. Inspection of pieces of the glass that have not been cleaned preparatory to specific gravity or other determinations, occasionally reveals a white substance embedded in some of the gas pores; some of this is taken to be (but not yet proved) residual flux material; much, however, consists of rounded quartz grains and a fine white clay comparable with that in the environment where the glass was found. Against this idea of the origin of Darwin Glass, it might be argued that comparable types of glass should occur from a heath, prairie, bush or forest fire. It is realized that temperatures developed in such fires are never high enough to fuse soils or rocks, and only baked soils have been observed after such fires, except in special circumstances. But it has been indicated that temperatures up to 1,800°C. can arise by drawing air through burning charcoal at high enough speed (Baker and Gaskin, 1946), and that an approach to such temperatures might be obtained in a forest fire, given the right set of conditions, such as a tall, hollow tree with an unobstructed path up its middle. In fact, these were the circumstances which caused the re-fusion of basalt and basalt soils at Mt. Franklin in Central Victoria, where such materials were evidently caught up in a burning tree trunk. An example of glass formed from the burning of a tree has been recorded from La Pine in Oregon (Pruett, 1939). There is thus evidence to show that sufficiently high temperatures can be obtained under special conditions to result in the formation of bleb-like and irregular, twisted pieces of natural glass, by the incineration of silica-bearing plants and fusion of any associated fine-grained mineral matter. This could apply particularly to Darwin Glass, since all the conditions are present that are requisite for such a mode of formation. The area of occurrence of the glass is 10 miles long and 6 miles wide, and it extends from a height of 1,240 feet above sea level at Ten Mile Hill and throughout the field of distribution, down to 500 feet above sea level. Similar pieces of the glass are found in the upper 12 inches or so of detrital surface material resting upon the quartzites and sandstones of the West Coast Range Conglomerate series, as in other parts where lying " directly on limestone in soil composed wholly of peat and the residual weathering products of that limestone—at Darwin " (Loftus Hills, 1915, p. 14). The necessary substances are therefore on hand for supplying the components of the Darwin Glass. Fluxes were also present for lowering the temperature of fusion of inorganic ash and adventitious mineral matter, and for promoting and facilitating the development of an alumino-silicate glass. The right amounts of natural fluxes were present, such as lime, ferric oxide, magnesia and the alkalies, while the sulphur that usually accompanies organic matter, also contributed to the promotion of the process. Reactions liberating gases such as CO_2, SO_2, water, absorbed air or the various gases evolved during the thermal decomposition of minerals, were probably responsible for the formation of the myriads of gas

pores present in the Darwin Glass, because the nature of the bubbles is such, and the flow structures are such that boiling of the glass does not seem to be indicated. Parts of the glass appear more solid than others in hand specimens, and some pieces are very vesicular, but thin sections of even the more dense pieces reveal many minute gas pores. This merely indicates that gas bubbles were driven off rather more readily from certain parts. The very abundant lechatelierite particles in Darwin Glass, are most frequently drawn-out along flow-line directions, indicating a fair measure of " running " of the glass while plastic, during which process, low-refraction lechatelierite was strung out as thin streaks in higher-refraction glass, along with a few elongated gas pores.

All the evidence so far accrued, seems to point to a terrestrial origin entirely, for Darwin Glass, and the method of formation which at present seems most suited, is that suggested above—smouldering peat bogs containing fluxes supplied the requisite conditions for fusion, while " button-grass " and finely divided, transported siliceous mineral matter and clay minerals supplied the ingredients to form a glass of acidic composition. It might be thought that the relative constancy of composition of Darwin Glass, as revealed by the four available chemical analyses, would militate against the above suggested theory of origin, but the fact cannot be overlooked that the various pieces of Darwin Glass have been scattered about somewhat by the limited Pleistocene glaciation in this region. This being so, the various pieces could then have been produced in much the same locale, from similar materials and under similar circumstances. The irregular shapes, twisted stalactitic forms and occasional blebs of Darwin Glass, added to its characteristic vesicularity (" frothiness "), offer no obstacles to the generation of this glass in the manner suggested, and such features are decidedly against a tektitic mode of origin. The streakiness of many pieces of Darwin Glass, evident from microscopic examination in oblique illumination, results from an intimate but incomplete mixing of drawn-out streaks of lechatelierite derived from the late fusion of quartz, with an aluminous glass fused just a little earlier than the silica glass from clay minerals.

It has been stated that the Aouelloul Glass is so like Darwin Glass, that if one knew the origin of one, a similar origin for the other could be inferred (Campbell Smith and Hey, 1952, p. 773). Even so, it is also as likely that two similar end products can be produced from similar materials in two different ways. The early confusion that existed in recognizing obsidian from tektites, is evidence of this sort of thing. The Aouelloul Glass has been regarded as resulting from meteoritic impact, the meteorite or swarm of meteorites being near-moldavitic in composition. Striking the sandstone of the Western Sahara with cosmic velocity, it is considered that such a glass would become largely fused and then intimately mixed with the sandstone which it also fused on impact, thus yielding the Aouelloul silica glass (Campbell Smith and Hey, 1952, p. 776). The writer can see no real justification for such a proposal, for the evidence of the study of australites in terms of the Aerodynamical Control Theory of shape development, leaves one without doubt that such bodies of glass were cold when they contacted the earth, and only very thin superficial front films were molten at any stage during ultra-supersonic atmospheric flight. Surely also, if a molten moldavitic glass is to be pictured as fusing and very intimately mixing with the desert sands, there should be transition layers between the two near the outer limits of such effects, as described by Ross for the trinitite, where the glass formed by the atom-bomb explosion produced a layer of glass 1 to 2 cms. thick overlying a bottom thicker layer of partly fused material which grades into the soil from which it was derived. The Aouelloul Glass, being associated with a crater that may be of meteoritic origin (Monod and

Pourquié, 1951), has evidently been formed by the high temperature fusion of material of comparable terrestrial parentage as that from which Darwin Glass was formed, which is not associated with any evidence of a meteorite crater or its usual associates. It would thus appear that two similar silica glasses from widely separated areas on the earth's crust, have, by two different methods of fusion, been derived from terrestrial matter of comparable character.

Chapter XVII.

THE STATUS OF TEKTITE ORIGIN. SUMMARY OF ESSENTIAL FACT AND THEORY.

Tektites (and natural silica glasses of as yet unproven origin), have been studied and discussed for the past 165 years, but still present subject matter for considerable debate. Additional finds of natural silica glasses have fairly regularly been made from time to time during the past 160 years in the previously known strewnfields and in newly found tektite fields, but little new data has been forthcoming from these finds, and little sufficiently important evidence that affects the tektite problem as it stands today.

Theories relating to tektite origin and the observed facts and data regarding their distribution, mode of occurrence, date of formation, time of arrival upon the earth's surface, physical and chemical nature, shape types and their development, sculpture, arcs and radii of curvature, &c., have been presented in some detail in the foregoing chapters with a view to bringing together as much of the interesting and essential fact and theory as is available, in order to trace the trend of tektite studies and indicate the state of the tektite question at the present time.

Many writers believe tektites are meteoritic in origin. The bulk of the evidence, as well as the bulk of opinion, favours this mode of origin, although several aspects of the problem still remain unsolved, so that the meteoritic origin theory does not satisfy all the critics in its entirety. Oswald (1936) summarized the position as it appeared to him twenty years ago, stating that there is nowadays no question as to tektite origin, most specialists in the subject being convinced of their meteoritic mode of development, and the dispute is now concerned only with their surface sculpture. A few years subsequently to the appearance of this summarizing statement, Barnes (1940a, p. 483) thought that Oswald's remark was a mis-statement, and that it only went to indicate the confusion of thought that existed on the subject as it stands today. It is to be hoped that the facts and evidence presented in these pages, with a long historical background of the gradual evolution of more rational theories of tektite origin, will serve to clarify what Barnes regarded as confusion of thought on the tektite problem, and that recent knowledge gained in the realm of studies of aerodynamical flow at supersonic velocities, as applied in a simplified form to the origin of such secondary shapes as those possessed by australites, will establish a meteoritic type of origin as the only feasible explanation of how tektites came to the earth, even though it is still conjectural from just where in the universe they originated.

The tektite question confronts the geologist, the astronomer, the physicist, the mathematician and the aerodynamicist with problems not readily solved, and no explanation has yet been advanced to fully account for all the observed facts and evidence. The chief point at issue is tektite origin. Finalization of the mode of origin centres around the question whether any of the characteristic features of tektites can be definitely assigned to cosmic processes, and whether their sculpture, composition and shape can be adequately accounted for by known terrestrial processes involving the chemistry, mechanics of formation, geology, &c. of these objects. Many controversial views have been expressed about these factors and all that they imply, without the end of the argument being yet in sight for all varieties of tektites from the several known fields of distribution. Some of the divergent theories have become invalid in the light of later investigations, but retain their interest in tracing the developmental history of tektite studies.

Hypotheses invoking artificial origin and the Gel Desiccation Theory have been satisfactorily eliminated. The ideas of distribution and origin according to the Great Circle Hypothesis have to be abandoned in view of later discoveries several degrees of arc off the originally postulated David—de Boer great circle, in view of two of the original components now known to be non-tektitic and only fortuitously lying on the great circle (i.e. schönite and Darwin Glass) and in view of the fact that the remaining three, authentic tektite groups, arrived upon the earth's surface at three different periods of the earth's Tertiary to Recent history.

In view of the fact that theories advocated prior to 1890 supporting a terrestrial origin, seemed to be unsatisfactory and irrelevant, the opinion was expressed that since no explanation of tektite origin by any terrestrial means appeared to fit all of the known facts, then tektites were probably of extra-terrestrial origin and represented glass meteorites. Criticism of this suggestion was at first strong, but meteoritic hypotheses later gradually gained in favour and came to be accepted and elaborated upon by Verbeek, Suess, Walcott, and others. The meteoritic theory of origin, in its several forms, however, depended largely upon negative evidence, and it was on this basis that the propounded ideas of such an origin continued to be criticized by upholders of a terrestrial origin, for they claimed the existence of more positive proofs favouring their hypotheses. Nevertheless, sufficiently numerous objections have been raised against the advocated theories based upon terrestrial sources for tektites. The most serious objections to any theory postulating origin from terrestrial volcanoes, for example, are (i) the absence in volcanic centres of rock types analogous to tektites, in all areas where tektites are found, (ii) the provincial distribution of australites according to their chemical composition—a distribution that could not have been accomplished by any known terrestrial processes, and (iii) the great distance of many tektites from volcanic areas. A further important objection lies in the significant differences in shape between such volcanic ejectamenta as bombs, lapilli, &c. and the secondary shapes developed upon australites anterior surfaces during atmospheric flight.

Objections to tektites having been formed electrically by fusion of dust in the atmosphere, or by fusion of soil and sand at the earth's surface in places where lightning is discharged, are principally based on shape, chemical composition and physical differences from such objects as "sand-tube" fulgurites and the like, that are known to have been formed by lightning earthing in sands.

Among adherents of a meteoritic type of origin for the tektites, there has been further controversial argument, based principally upon whether the tektites were formed in the atmosphere, by several suggested means, from a visitor from outer space, or whether the tektites came in from outer space themselves as individual entities representing the components of showers of glass drawn to earth at different periods of earth history. One theory that received support from such workers as Goldschmidt, Michel, Lacroix and Fenner, postulated development of tektites from the oxidation of light metal meteorites in the earth's atmosphere, and another theory that has received no support, advocated tektite derivation as plastic sweepings from an earthward-moving metallic meteorite. Because of many limitations to such theories, and the fact that the many suppositions cannot be founded on a secure basis, such means of meteoritic origin are gradually falling out of favour.

A very important aspect of tektite origin requiring further consideration and verification is whether tektites, if, as seems most likely, they did come from an extraterrestrial source, entered the earth's atmosphere as cold, independent

bodies, or whether they came into the atmosphere as plastic bodies, or whether they were generated instantaneously as hot, fluid bodies within the atmosphere. The clue to these questions seems to lie in detailed examinations of the physics, &c. of the Australian tektites, which reveal undoubted evidence of having been subjected to two periods of melting—(a) a complete melting in their primary source and the generation of a few typical initial forms, and (b) a secondary phase of superficial front-surface melting with the resultant modification of those initial shapes. On the basis of the australites then, it seems to the writer more logical to regard tektites as having entered the earth's atmosphere from outer space at cosmic speeds and as cold, independent bodies. It then becomes necessary to invoke some means whereby they could become sufficiently hot to superficially melt on their forward surfaces. In the terms of the Meteoritic Oxidation Theory, the necessary heat for the development of completely molten bodies, is supplied by chemical combustion in light metal meteorites, so that if this theory could be proved correct, tektites would then represent the residual, incompletely volatilized residual silicate portions of the postulated light metal meteorites. It has been shown, however, that there is little likelihood that the australites were completely molten bodies during atmospheric flight, and the cause of heating is thus friction between cold, glassy objects travelling at high speed through a partially resistant medium—the air, and under such circumstances, similar general explanations are required for the tektites as are already in existence for the iron and stony meteorites. It has been suggested in the foregoing pages, that Lindemann's (1926) ideas concerning such phenomena, go a long way towards supporting the idea that tektites were cold when they first encountered the earth's atmosphere, and also settle certain difficulties raised by critics who maintained that frictional heat would be insufficient in magnitude to cause the melting of tektite glass. All that is required of frictional heat, for the australites at least, is that very thin films of glass become molten at any one time on their forward surfaces, and this can be adequately supplied in terms of Lindemann's reasonings. The Meteorite Splash Theory for tektite origin as put forward by Spencer is by no means applicable to the shapely australites with their freedom from nickel-iron spheres such as are found associated with "impactites," hence this theory can be ruled out in its application to the authentic tektites, although it adequately explains the natural silica glasses that are found associated with meteorite craters.

It has been pointed out herein, that the dispute regarding the sculpture of tektite surfaces, involves two schools of thought—on the one hand are those convinced of the origin of tektite sculpture from etching by chemical action in soils or clays of regions where tektites are recovered, exponents of this theory including such authors as Van der Veen, Escher, Michel, Lacroix and Fenner. On the other hand is the school of thought invoking the development of tektite sculpture from processes at work in the atmosphere during earthward flight, or even during some pre-atmospheric stage of flight. Adherents to this theory were Suess, Linck, and others.

The idea of tektite sculpture developing from the chemical activity of weak acids in soils, purely and simply, is not convincing for such examples as the australites. Etching by purely terrestrial phenomena usually implies cracking, collisional bruising and subsequent chemical corrosion in acid soils for most tektite types. The writer considers that etching has played some part in bringing out the sculpture markings on certain tektite surfaces, but at the same time, it seems obvious that the same process has also caused the destruction or partial obliteration of finer sculpture features, under certain circumstances. It is doubtful whether it would be correct to picture tektites as balls and blobs of

glass with absolutely smooth outer surfaces lacking sculpture patterns, prior to landing upon the earth's surface, especially as they have such contorted and complex internal flow line patterns. Etching in soils could scarcely be entirely responsible for such sculpture features as vermicular bubble tracks, collapsed bubble craters with inrolled lips, and the like, even with the aid of cracking and collisional bruising. It is thus apparent that a sculpture pattern already existed on the surfaces of tektites before they entered the earth's atmosphere, and that this pattern was essentially a manifestation of the pre-formed internal structures. Some of these patterns in some of the tektites from the different strewnfields, were partially destroyed or modified during atmospheric flight. The part played by etching upon the earth's surface, was purely and simply one of accentuating the already existing sculpture features, or sometimes, destroying them.

Finally, it would appear that the nature of distribution and mode of occurrence, the shape and form of tektites, the absence of crystallites from all accepted true tektites, their highly complicated external and internal flow line patterns and the nature of sculpture patterns, added to the recently elaborated ideas of the part played by aerodynamics at high speeds of flight through the earth's atmosphere, all provide a convincing array of evidence that weighs heavily against all and sundry hypotheses of a terrestrial origin for tektites. Theories of extraterrestrial origin have disagreed in details among themselves from time to time, but the general principle of a meteoritic type of origin is one entitled to acceptance, even though difficult to prove beyond doubt. Many difficulties arise as to the means of testing and proving such a theory, in order to ascertain whether it is adequate to explain all the known facts—a condition that terrestrial origin hypotheses are even less capable of bringing about.

It has been argued that the question would only be solved if someone competent to record all the facts, could witness the actual fall of tektites from the skies. It has also been argued that attempts to solve the problem should not be left to such an element of chance—such a chance may never arise.

The writer considers that without awaiting a probable fall of tektites that may never transpire under circumstances satisfactory to all the critics, the solution to the problem of tektite origin may now rest entirely with the physicist and aerodynamical engineer. The geologist has accumulated a great wealth of information regarding tektites as they occur in the field and as they appear in hand specimens and under the petrological microscope. He has had to introduce assumptions of uncertain validity into some theories advanced with the known facts as a basis; quite a number of speculations, however, have added little of value to the problem in general, except perhaps other than by stimulating further thought upon matters of origin. Before the mystery of tektite origin draws nearer to a successful solution, more definite information must be sought concerning the original mass and shape of individual tektites from the sundry tektite strewnfields, more must be found out concerning their probable velocities through the earth's atmosphere, and on the rate of heat transference in them under the conditions dictated by a meteoritic origin and hence by their journey through the atmosphere at high speeds. Further details are required concerning the effects of the resistant atmosphere on the forward surfaces of tektites, if they are to be regarded as bodies that travelled earthwards at supersonic speeds, for it is evident that certain tektites such as the australites, present features indicating secondary melting effects that have so far not been detected on other types of tektites. Many of these problems appear to be beyond explanation with the known facts as a basis, although aerodynamical control during high speed flight, seems capable of explaining many features of tektites. The background question still remains, however—from whence in extraterrestrial space did the tektites originate?

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INDEX OF AUTHORS, ANALYSTS, COLLECTORS, ETC.

Z.

INDEX OF LOCALITIES.

Abbreviations.

Ar. = Arabia. Bo. = Bohemia. C.A. = Central Australia. Col. = Colombia. F.I.C. = French Indo-China. F.M.S. = Federated Malay States. Ger. = Germany. I.C. = Ivory Coast, Africa. Mo. = Moravia. N.E.I. = Netherland East Indies. N.G. = New Guinea. N.S.W. = New South Wales. N.T. = Northern Territory of Australia. N.Z. = New Zealand. P. = Peru. P.I. = Philippine Islands. Q. = Queensland. S.A. = South Australia. T. = Tasmania. U.S.A. = United States of America. V. = Victoria. W.A. = Western Australia.

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INDEX OF SUBJECT MATTER.

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PLATE I.—Sculpture of billitonites (A to E) and australites (F to N).

A to C—rounded and elliptical forms (× 1·5). Island of Billiton, N.E.I. (Melbourne University Collection—photos. by J. S. Mann).

D to E—pear-shaped forms collected by Wing Easton (after Lacroix, 1932). Showing flow lines, "navel", vermicular and circular U-shaped grooves.

F to H—elongated australite core with bubble crater, short radial grooves on posterior surface (F) and flow grooves in equatorial zone (H) parallel to flight direction (weight—95·85 grams), from Kaniva, Victoria (Melbourne University Collection). Approx. nat. size.

L to N—elongated australite with sharp rim separating posterior from anterior surfaces without the development of a flaked equatorial zone. Posterior surface (L) with vitreous lustre, a few bubble pits and occasional compressed flow grooves (weight—88·45 grams), from Corop, Victoria. (Melbourne University Collection—photos. by J. S. Mann.) Approx. nat. size.

PLATE I.

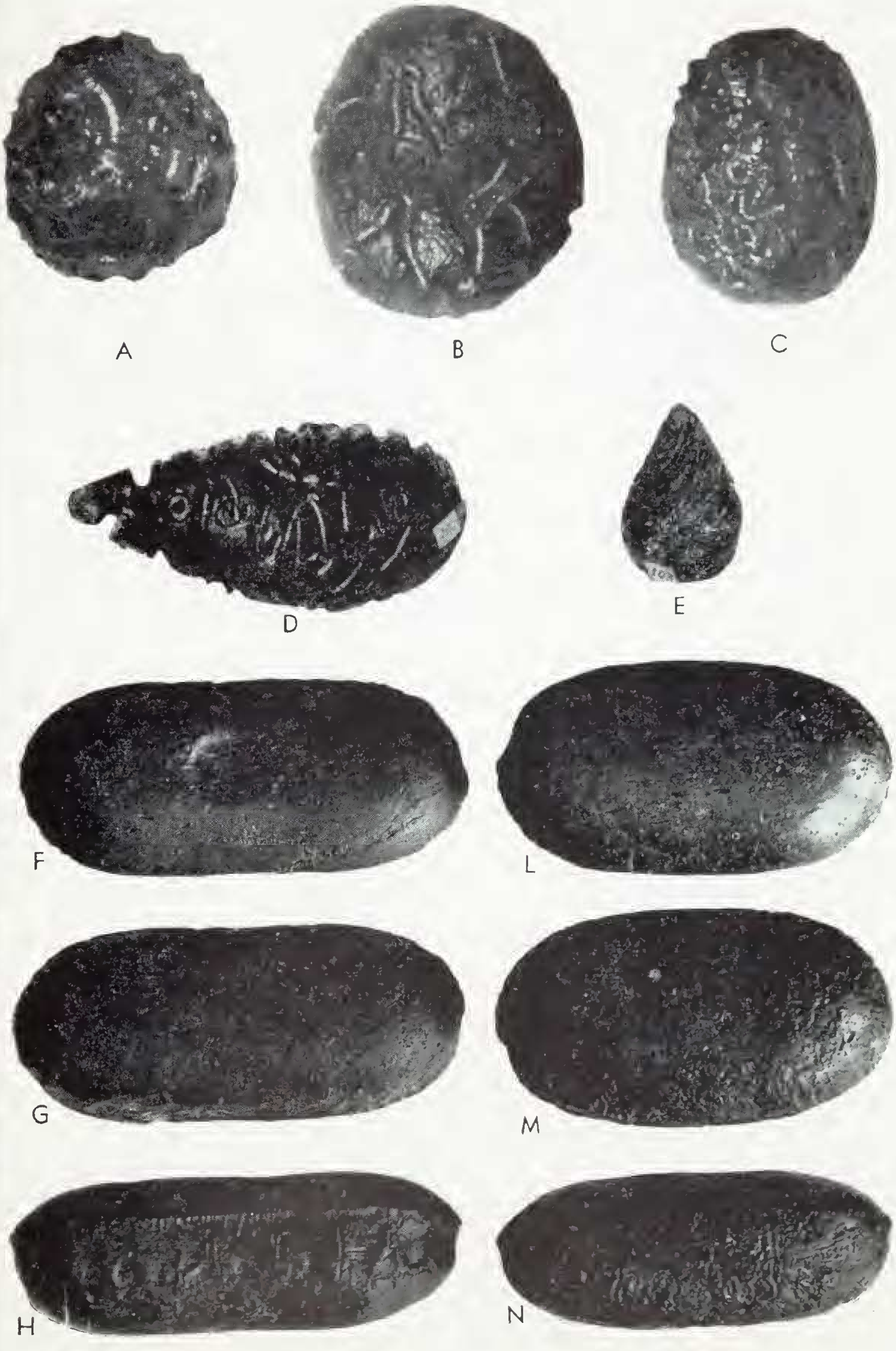


Plate II.—Surface structures of indochinites ("corrosions" of Lacroix).

1, 2, 4 and 5—sculptured "plaques" with flow lines (× 0·6).

3—sculptured pear-shaped form with channels (× 1·4).

6 and 7—flattened pear-shaped forms with bubble pits (× 1·4).

8 and 9—tear-shaped forms with vermiform gutters and cupules; large cupules containing smaller ones in fig. 8 (nat. size).

10—"cudgel" with vermiform grooves on under part (nat. size).

11—tear-shaped form with drawn-out canals on tail and cupules on gibbosity (nat. size).

12—disc, sculptured with vermiform grooves diverging from a centre.

1 to 7 and 11 from Lang Bian, Indo-China; 8 to 10 and 12 from Tan-hai Island (after Lacroix, 1932).

PLATE II.

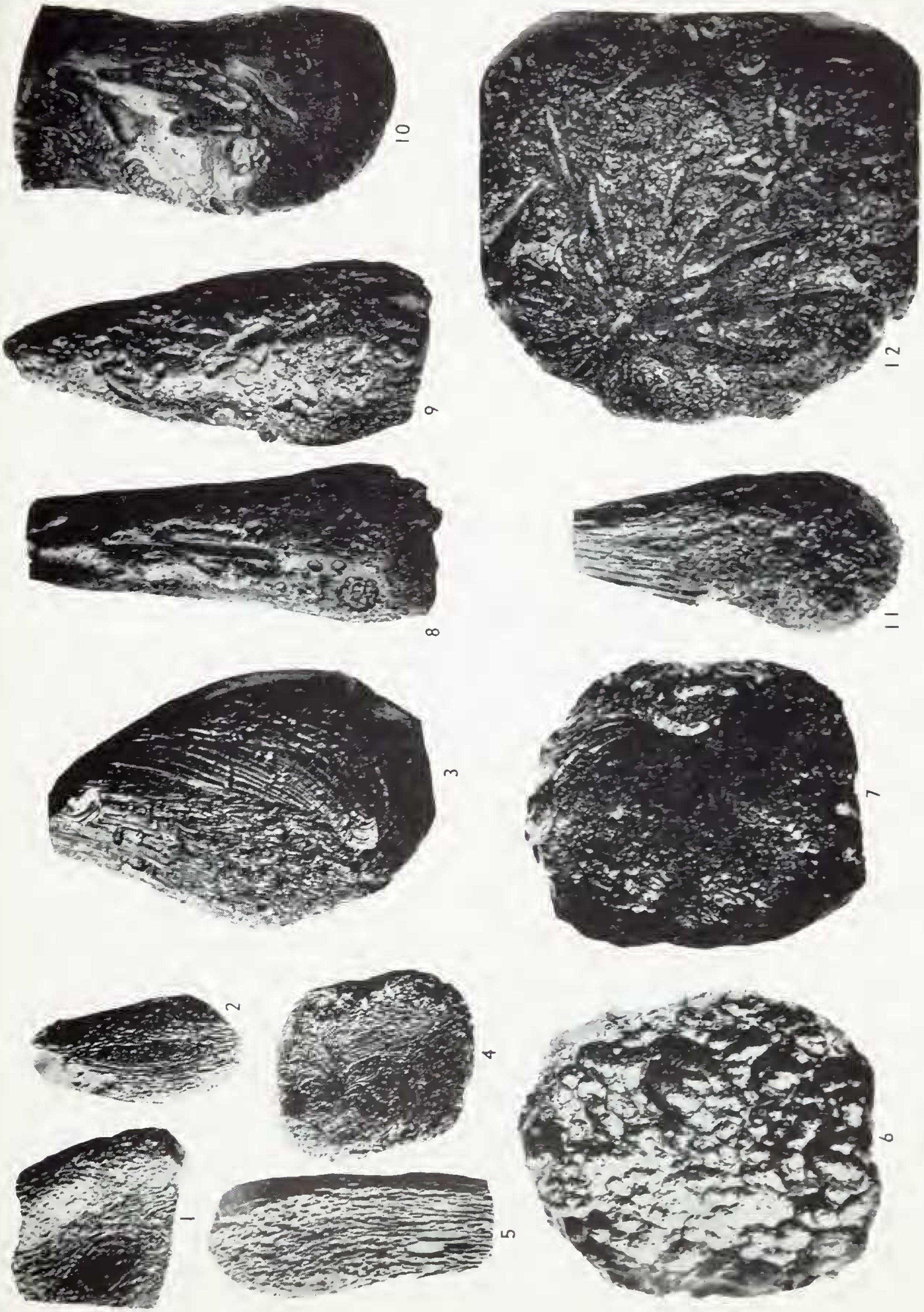


PLATE III.—Sculpture of moldavites.

1a to 1c—regular, disc-shaped form showing pitting, from Skrey-Dukowan, Moravia.

2a to 2c—core fragment with pits, from Slavitz, Moravia.

3a to 3d—cone-shaped form with pits and grooves, from Skrey, Moravia. All natural size (after F. E. Suess, 1900).

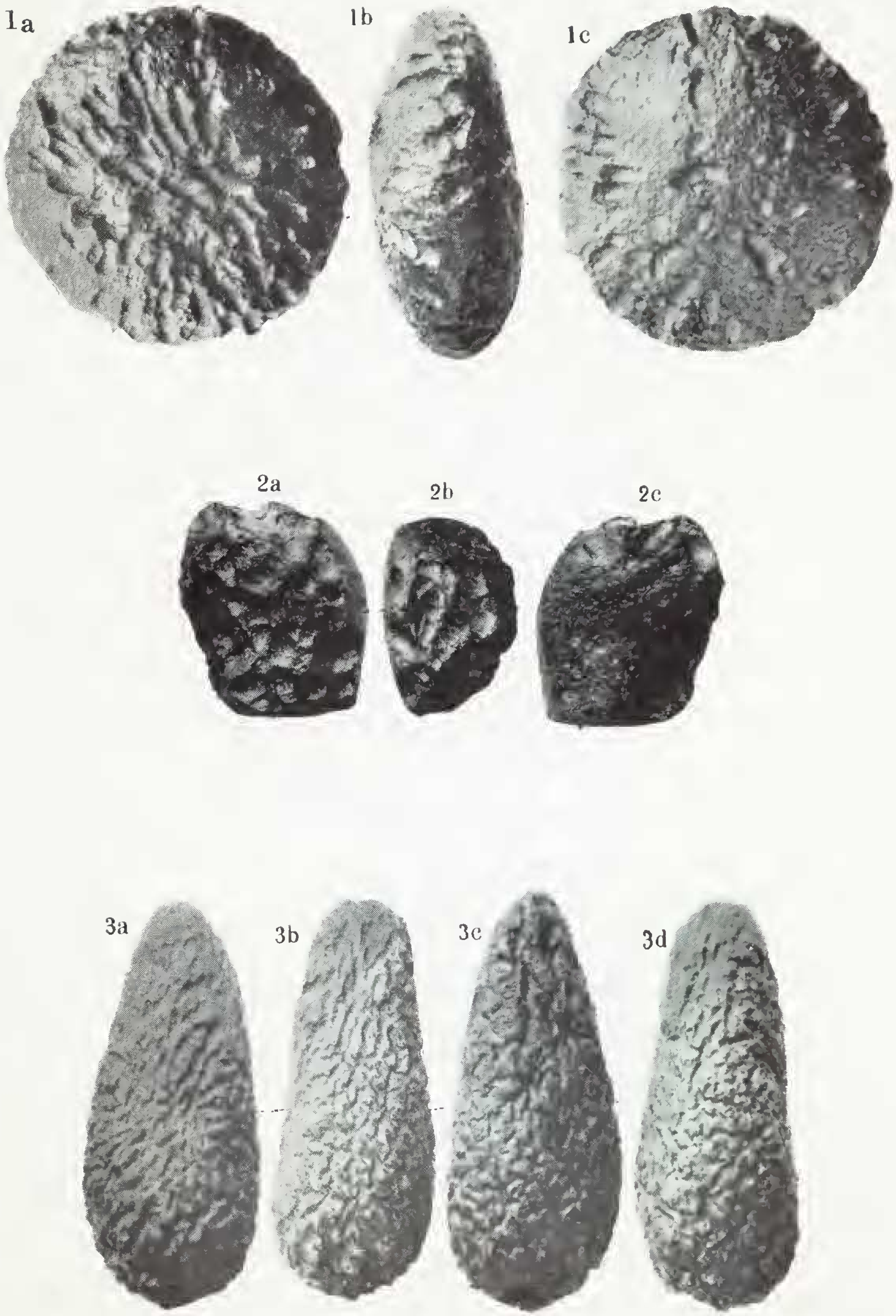
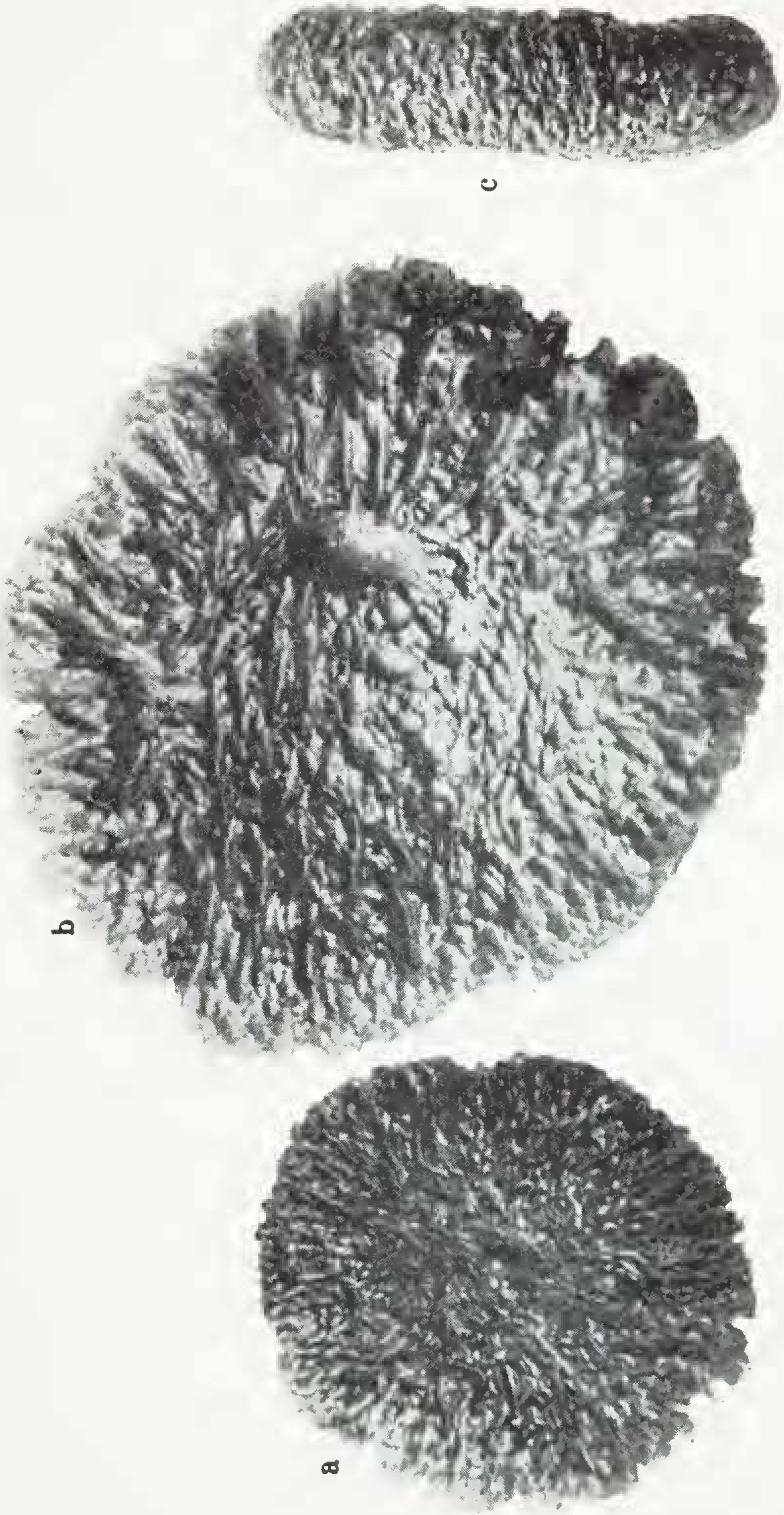

1a
1b
1c
2a
2b
2c
3a
3b
3c
3d

PLATE IV.—Sculpture of moldavites.

a to c—thick, corroded, scaly chips with grooves, from near Budweis, Bohemia.

Natural size (after F. E. Suess, 1900).

PLATE IV.



c

b

a

Plate V.—Sculpture of large and small australites.

A—bubble-pitted posterior surface of non-flanged elongated form (× 2·5).

B—posterior surface of round core with flow lines, grooves and pits (× 2·5).

C—posterior surface of round core with smooth flow-lined patches ("swirls") and bubble-pitted areas (× 2·5).

D—"pine-seed" type (weight = 0·533 grams). National Museum Collection, Melbourne.

E—disc-shaped form (weight = 0·3184 grams). Melbourne University Collection.

F—narrow, boat-shaped form (weight = 0·4362 grams). Melbourne University Collection.

Sketches of posterior (upper) surfaces and sectional aspects of each of the forms D to F are shown. A and B from Hamilton, Victoria; C from Condah, Victoria; D, E and F from Stony Creek Basin, near Hall's Gap, Grampians, Victoria.

(A to C after Dunn, 1912; D to F after Skeats, 1915.)

PLATE V.

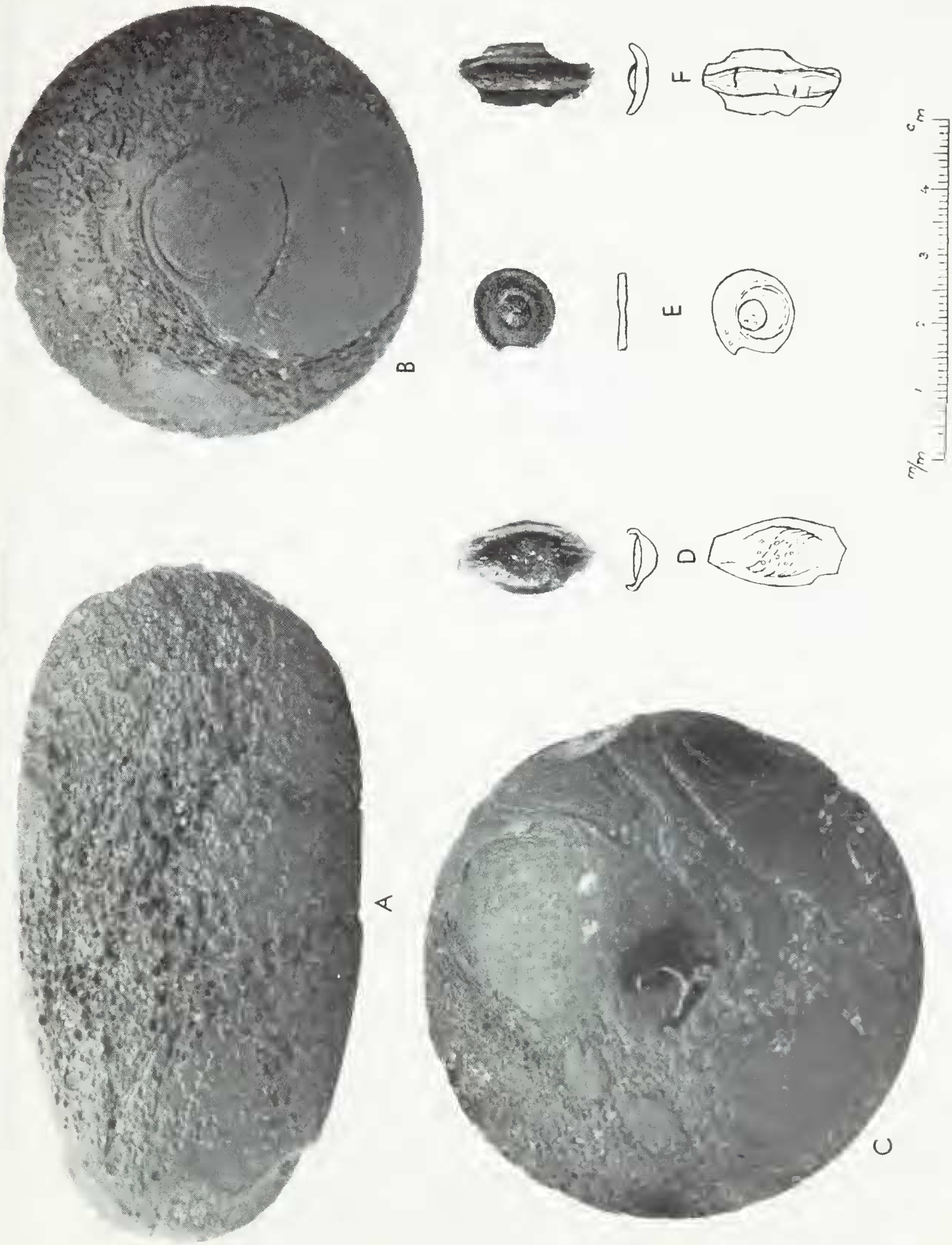


PLATE VI.—Sculpture of indochinites.

1 and 2—tear-shaped forms with flow lines and bubble pits, from Lang Bian, Indo-China.

3 and 4—pear-shaped forms with flow grooves and pits, from Tan-hai Island (× 0·87).

5—"baton" (× 0·94).

6—deformed "pear" (× 0·91).

7—"pear" (× 0·75).

8—"tear" (× 0·75).

9—"tear" with long "shank" (× 0·75).

5 to 9 from Dalat, French Indo-China (after Lacroix, 1932 and 1935b).

PLATE VI.

PLATE VII.—1 to 12—Sculpture of bediasites (forms coated with ammonium chloride to bring out surface features) (all × 0·875). From Texas, U.S.A. 13 to 19—Photomicrographs of lechatelierite particles and bubbles in tektites (all × 62·5).

1—pear-shaped form with well-developed flow structure.
2—spall fragment.
3—small spall surfaces contrasted with deeply etched surfaces.
4—smallest bediasite in Barnes' collection.
5—long, deeply pitted form.
6—long, smooth form.
7—spall fragment.
8—largest and most highly spalled bediasite in Barnes' collection.
9—spall fragment illustrating flow structure.
10—smooth, spherical type.
11—"gumdrop" type.
12—form showing U-shaped furrows.
13 and 14—lechatelierite particles in indochinites; black spherical objects are bubbles, some of which are included in the lechatelierite.
15—lechatelierite particles in a bediasite.
16—elongated lechatelierite particle parallel to flow structure in a bediasite.
17—hooked and elliptical lechatelierite particles in a bediasite.
18 and 19—lechatelierite particle between crossed nicols, illustrating nimbus quartered by brushes; (fig. 19 rotated 45° from the position shown in fig. 18) (after Barnes, 1940a).

PLATE VII.

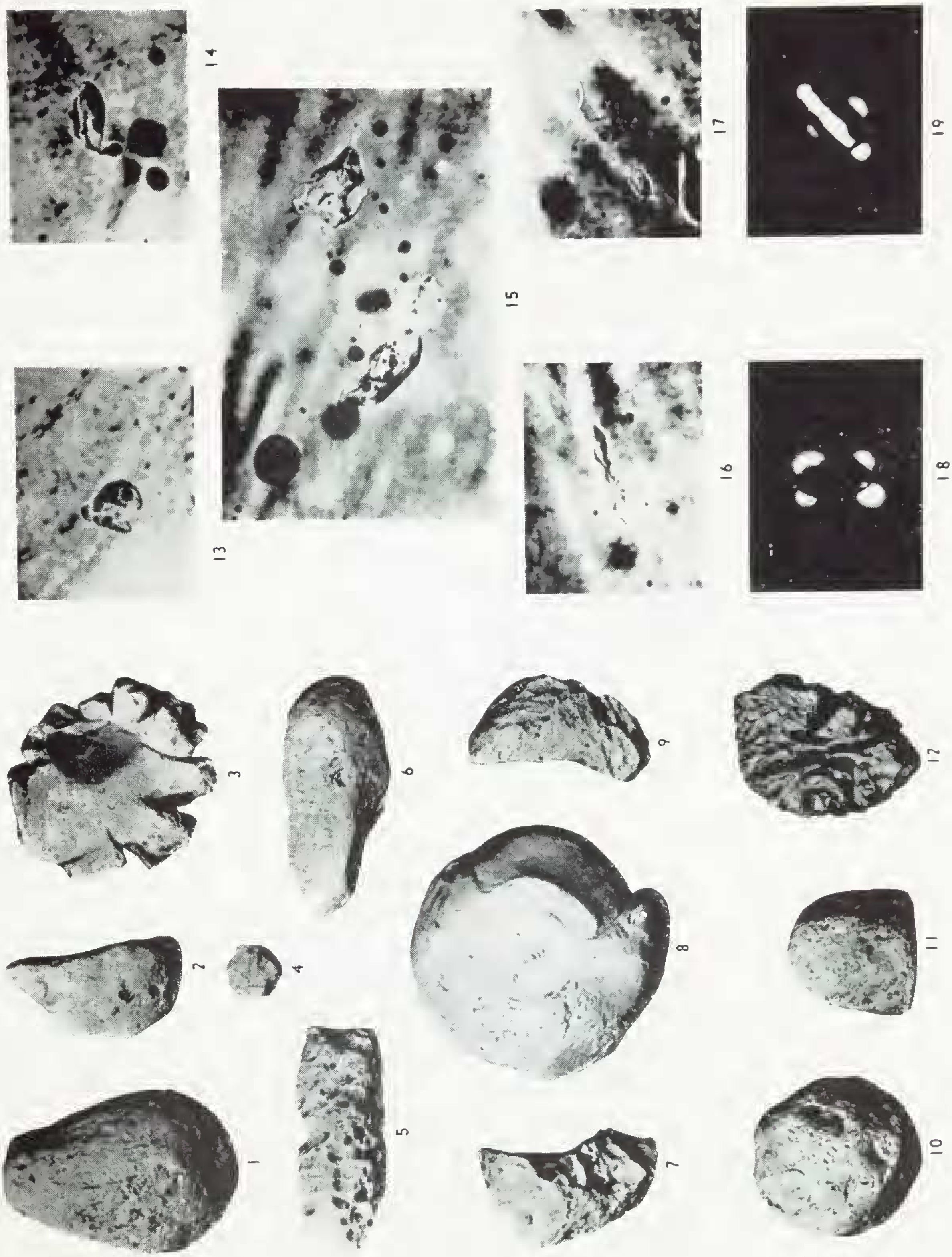


Plate VIII.—Exceptionally wide flange on button-shaped australite (weight = 4·59 grams).

A—bubble-pitted and flow-lined posterior surface.

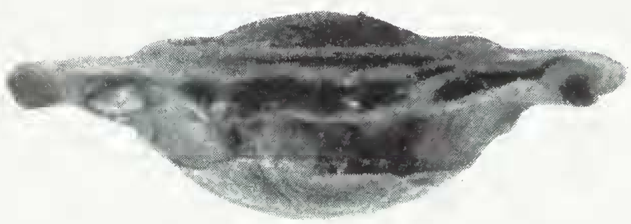
B—side aspect showing nature of arcs of curvature of posterior and anterior surfaces, and flat character of flange.

C—anterior surface with flow lines and flow ridges.

From Mt. Cameron water-race, near Gladstone, N.E. Tasmania (× 2·3). (Melbourne University Collection—photos. by J. S. Mann).

PLATE VIII.

A



B

C

PLATE IX.—Structures of flanged, elongated australites.

A—anterior surface of dumb-bell-shaped form ($\times$ 2), with flow ridges transverse in waist region, parallel with outline of form on bulbous ends, and crinkled in equatorial regions.

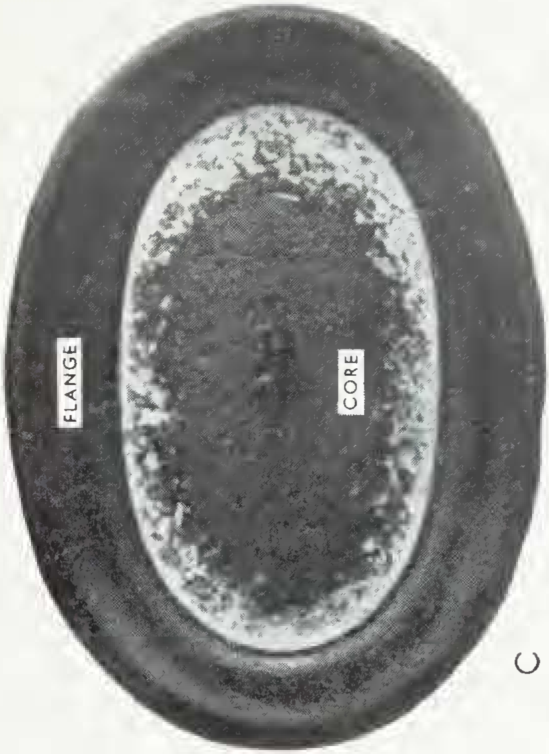
B—side aspect of A, showing relationship of flange to posterior (on left) and anterior (on right) surfaces.

C—posterior surface of boat-shaped form ($\times$ 3), showing complete flange with even outline; bubble-pitted and flow-lined core. White areas represent sand and clay lodged in bubble pits near junction of flange and body.

D—anterior surface of C, showing concentric flow ridges.

Both specimens from Mt. William, Grampians, Victoria (after Dunn, 1912).

PLATE IX.



C

D

B

A

Plate X. External and internal features of australites.

A—Non-abraded boat-shaped core form (weight = 29·48 grams), showing flaked equatorial zone with flow grooves, sharply defined rim between posterior surface and flaked zone; bubble-pitted posterior surface. ($\times$ 3·5). (Photo. by J. S. Mann).

B—Section through button-shaped australite, showing complex internal flow structures in body portion, and coiled flow structures in flange structure. (posterior surface uppermost). ($\times$ 5·5) From Port Campbell, Victoria (after Baker, 1944).

A

B

PLATE XI.—Internal flow structures of various australite shapes (posterior surfaces uppermost).

A—radial section of button-shaped form showing cracks infilled with ferruginous clay (black) and small quartz grains (× 3·3).

B—cross section of boat-shaped form cut normal to long axis (× 5·8).

C—cross section of lens-shaped form with bubble crater exposed on anterior surface (× 5·8).

D—longitudinal section of oval-shaped form showing newly formed flange and remnant of former flange. Collapsed bubble crater with pinnacle of glass, on anterior surface. Flow lines in body portion trend towards newly developed flange (× 6·7).

E—cross section of lens-shaped form showing flow lines leading to bubble pits on posterior surface, and sharply transected on anterior surface (× 5).

All from Port Campbell, Victoria (after Baker, 1944).

PLATE XI.

Plate XII. Enlarged sections of flange showing nature of junction between flange and body. Spirally coiled flow lines in flange contorted in "chin" regions; flow lines near "seat" region truncated in "flow-wave" structures on anterior surface.

A— ($\times$ 24); B— ($\times$ 20).

Both specimens from Port Campbell, Victoria.

(Photos. by J. S. Mann.)


A
SURFACE
POSTERIOR
FLOW LINES
SURFACE
ANTERIOR


B
SURFACE
POSTERIOR
SURFACE
FLOW LINES
ANTERIOR

Plate XIII.—Crystal, glass and gas inclusions in the (?)tektite from Paucartambo, Peru.

1—form and external structure of the (?)tektite (× 1/3).
2—void with bubble-shaped termination (× 4·5).
3—gas bubbles formed by heating the edge of the glass to 900° C. (× 16).
4—andalusite (× 70).
5—sillimanite (× 190).
6—wollastonite (× 106).
7—wollastonite and (?)felspar intergrowth (× 230).
8—scapolite (× 230).
9—twinned scapolite (× 106).
10—orthoclase (adularia-like) (× 70).
11—Carlsbad twin of orthoclase (× 230).
12—andesine with andalusite intergrowth (× 37).
13—zircon (× 230).
14—aegerine-augite (× 230).
15—common augite (× 140).
16—biotite (× 230).
17—quartz and zircon (× 300).
18—spinel(?) (× 150).
19—glass in glass, surrounding (?)scapolite (× 230).
20—glass in glass, surrounding (?)andesine (× 150).
21—glass in glass, with *a* crystal residue (× 230).

(After Linck, 1926.)

PLATE XIII.


Fig. 14
Fig. 13
Fig. 12
Fig. 19
Fig. 17
Fig. 18
Fig. 15
Fig. 16
Fig. 21
Fig. 20
Fig. 4
Fig. 2
Fig. 1
Fig. 3
Fig. 5
Fig. 6
Fig. 11
Fig. 10

PLATE XIV.—Tektites with large bubbles.

1a and 1b—external surface of hollow australite (nat. size), from Kangaroo Island, South Australia (after Suess, 1900).

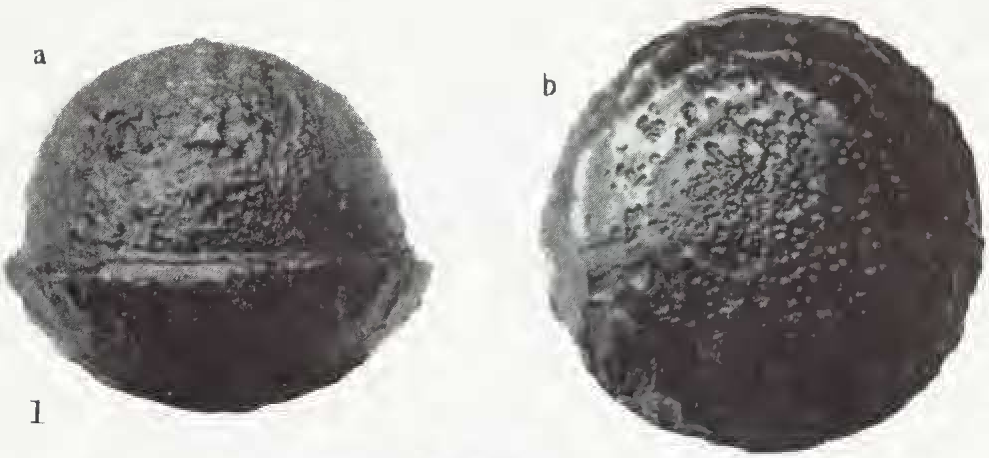
2—interior of hollow australite with double bubble showing dividing septum. Clear reflections from walls of bubble indicate high degree of "hot polish" ($\times$ 2), from Charlotte Waters, Central Australia (after Dunn, 1912).

3—diametrical section of sphere-shaped indomalaysianite (Damour specimen), showing large internal bubble, from Pahang, Malaya (after Lacroix, 1932).

PLATE XIV.

a

b



1

2

3

PLATE XV. Small bubble pits on the surfaces of various forms of australites.

1A and 1B—posterior surface and side aspect of boat-shaped core from Ellerslie, Victoria (weight = 47·716 grams), showing finely pitted posterior surface with large bubble crater to which numerous bubble tracks lead from the flaked equatorial zone (1B).

2—anterior surface of weathered elongated core form ploughed up at Polkemmet East, near Horsham, Victoria (weight = 31·885 grams), showing rare bubble pits and minute etch pits.

3A to 3C—posterior, anterior and equatorial aspects of slightly oval-shaped core form from Ellerslie, Victoria (weight = 27·535 grams), showing more numerous bubble pits on posterior surface (3A).

4A and 4B—button-shaped form (weight = 4·83 grams) showing pitted posterior surface of body portion and smooth posterior surface of flange portion; three flow ridges discernible on anterior surface (4B).

5—dumb-bell-shaped form with minute remnants of flange (weight = 1·67 grams), showing finely pitted and flow-lined posterior surface.

6—lens-shaped form (weight = 2·45 grams), showing finely pitted posterior surface.

Specimens 4 to 6 from Inverell, New South Wales.

(Specimens 1 to 6 in Melbourne University Collection.)

(Photos. by J. S. Mann.)

Plate XV.

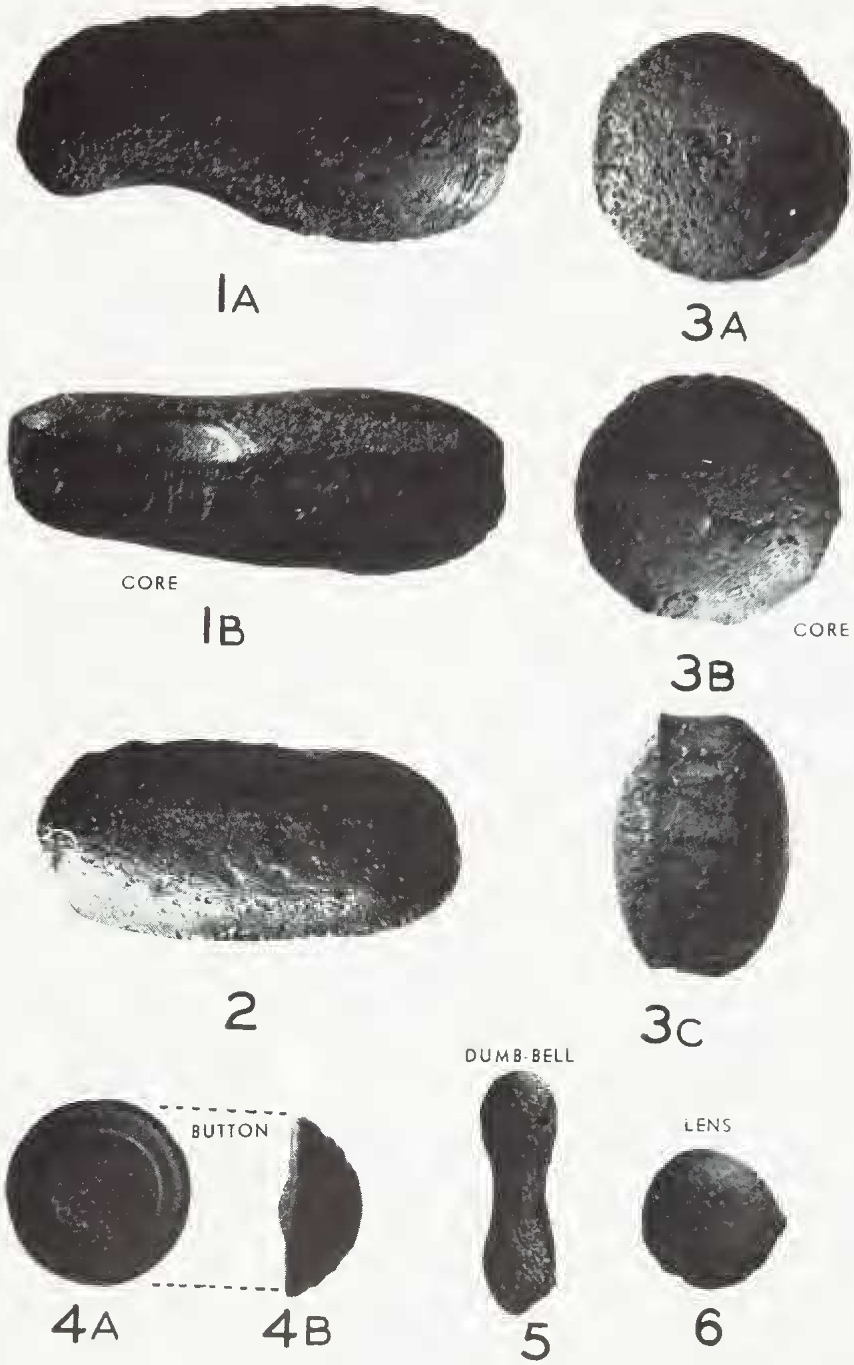


PLATE XVI.—Gas bubble craters and blisters on indochinites (nat. size).

1—ellipsoidal bubble crater with long axis parallel to elongation direction of the tektite.

2—spherical bubble craters on the gibbosity of a tear-shaped form.

3—bubble craters with flow-lined walls.

4—elongated protuberance due to enclosed bubble.

5—regularly-shaped bubble crater, resembling a dish.

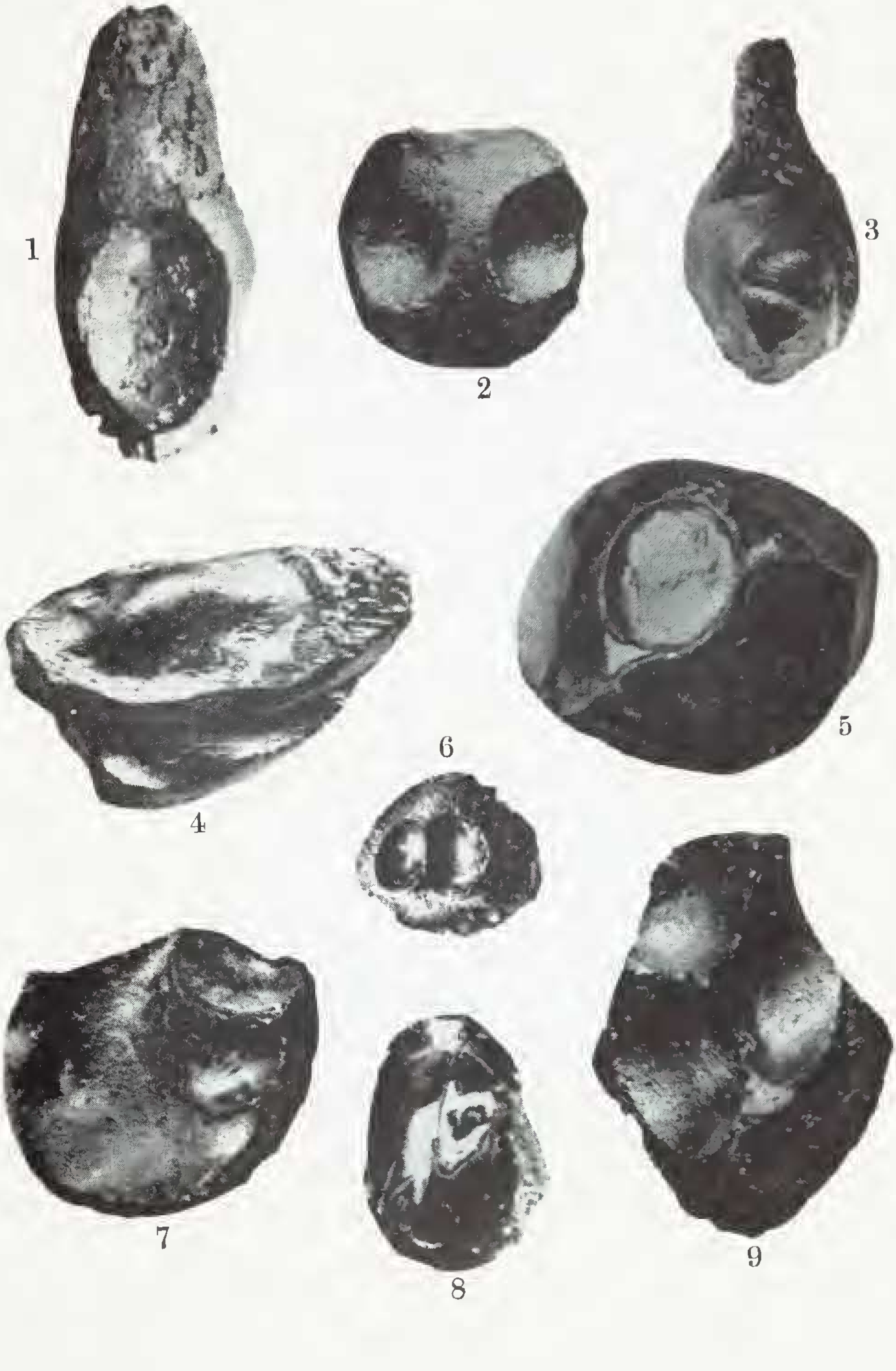
6—bubble craters separated by a narrow septum of glass.

7—interrupted bubble craters.

8—artificial fracture surface of an indochinite.

9—union of three bubble eraters.

1 to 4 and 6 to 9 from Kwang-Chow-wan; 5 from Pia Oae, F.I.C. (after Lacroix, 1935b).



1 2 3 4 5 6 7 8 9

Plate XVII.—Photomicrographs of minute gas bubbles in indochinites.

1—numerous small bubbles, some partially elongated; particle of lechatelierite near centre of photograph (× 73).

2—elongated bubbles drawn out to acute points along flow-line directions (× 24).

Both examples from Séan Tô, Hai-nan Island (after Lacroix, 1935b).

1

2

PLATE XVIII.—Sculpture on irregular forms of indochinites 1 to 5 (× 0·7); 6 (× 1·3); 7 to 10 — enlargements of sculpture).

1—deep gutter on fragment, evidently accentuated by natural etching.

2—plate with deformed bubble craters resulting from flattening of fluidal glass.

3—linear arrangement of channels; sculpture dependent upon internal character.

4—intersecting vermiform gutters disposed in two directions at right angles.

5—anticlinal "plissure" (pucker) in channels; sculpture dependent upon internal character of the glass.

6—elliptical flow lines and elongated cupules (flow-lined area comparable with "swirls" on australite posterior surfaces).

7—annulated and vermiform gutters (× 1·75).

8—hemispherical and hemi-ellipsoidal cupules, coalescing where crowded (× 1·4).

9—hemi-elliptical cupules (× 1·7).

10—secondary cupules on surface walls of large cupules (× 1·8).

1, 2 and 6 to 10 from Kwang-Chow-wan; 3, 4 and 5 from Hai-nan Island. (After Lacroix, 1935b.)

PLATE XVIII.

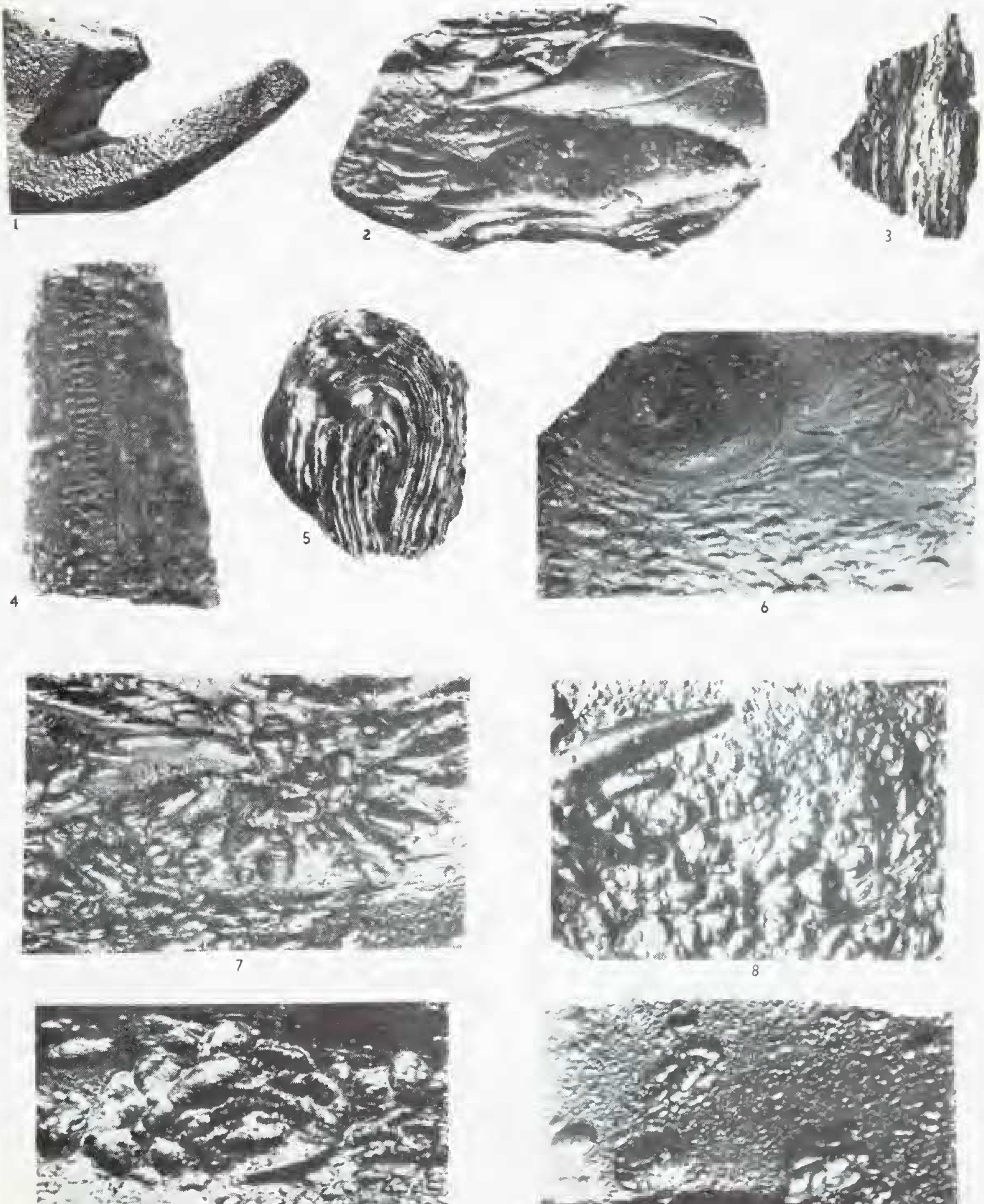


PLATE XIX.—Sculpture and shape of rizalites Cylindrical, dumb-bell, oval and spheroidal forms with characteristic pitted surfaces. Billitonite-like grooving on some forms (Nos. 13 to 15), bubble crater on No. 11. No. 10 resembles some of the Java tektites, Nos. 6 and 8 resemble abraded australites.

From Rizal Province, Luzon, Philippine Islands (after Beyer, 1935).

PLATE XIX.

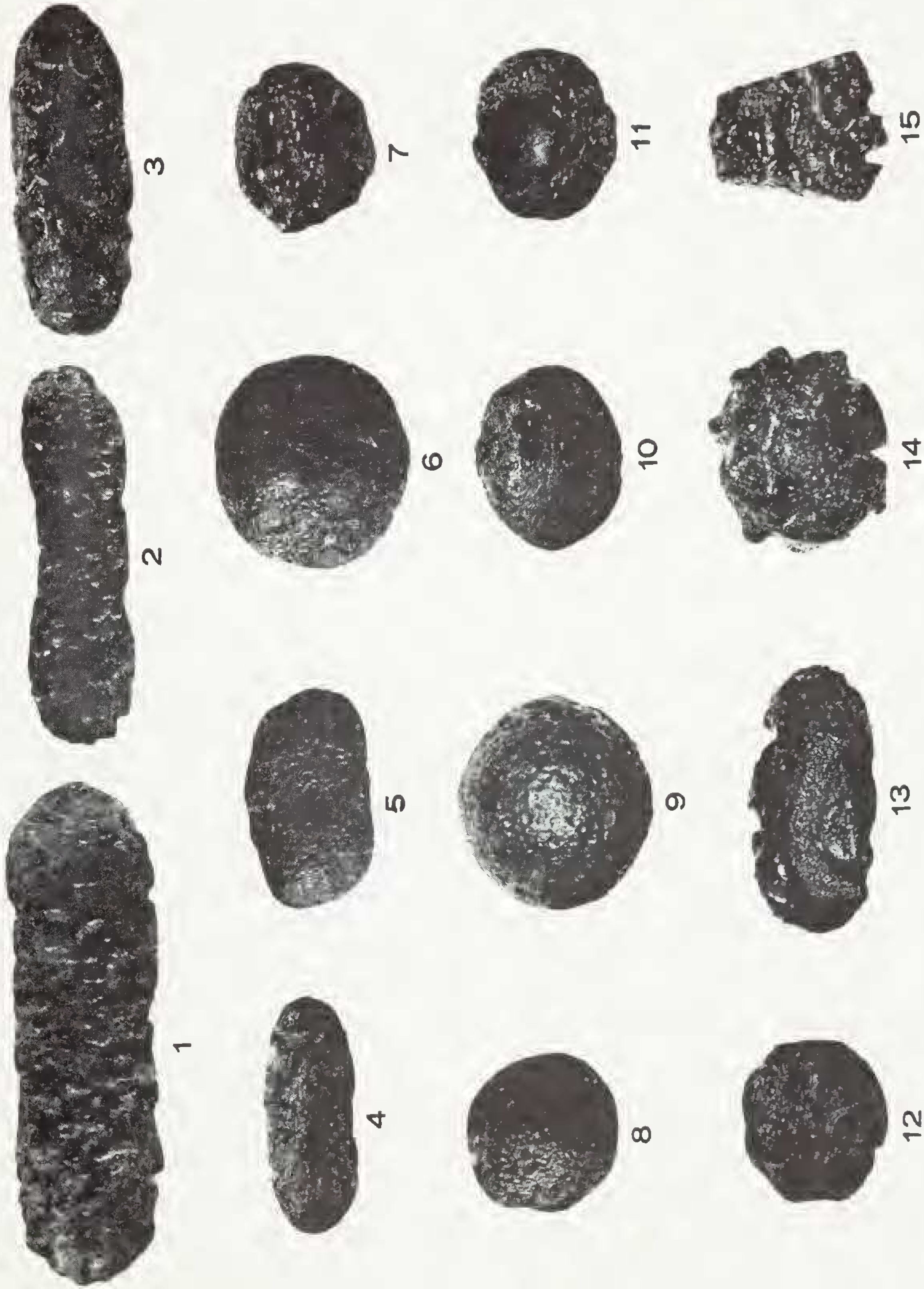


Plate XX.—Lead bullets flattened by firing against a metal target ($\times$ 1·5) showing shapes bearing some resemblance to flanged australites. Straw silica glass and artificially etched indochinite.

A and C—back surfaces of flattened bullets showing flange-like structure.

B—front surface of flattened bullet showing wavy flow marks near outer edge.

D—straw silica glass from Ballarat District, Victoria (approx. nat. size) showing glassy bleb-like character and impressions of incinerated straw (Victorian Mines Department Collection).

E—flow lines made prominent on indochinite glass by treatment with hydrofluoric acid.

(A to D—photos. by J. S. Mann; E—after Lacroix, 1932.)

PLATE XX.

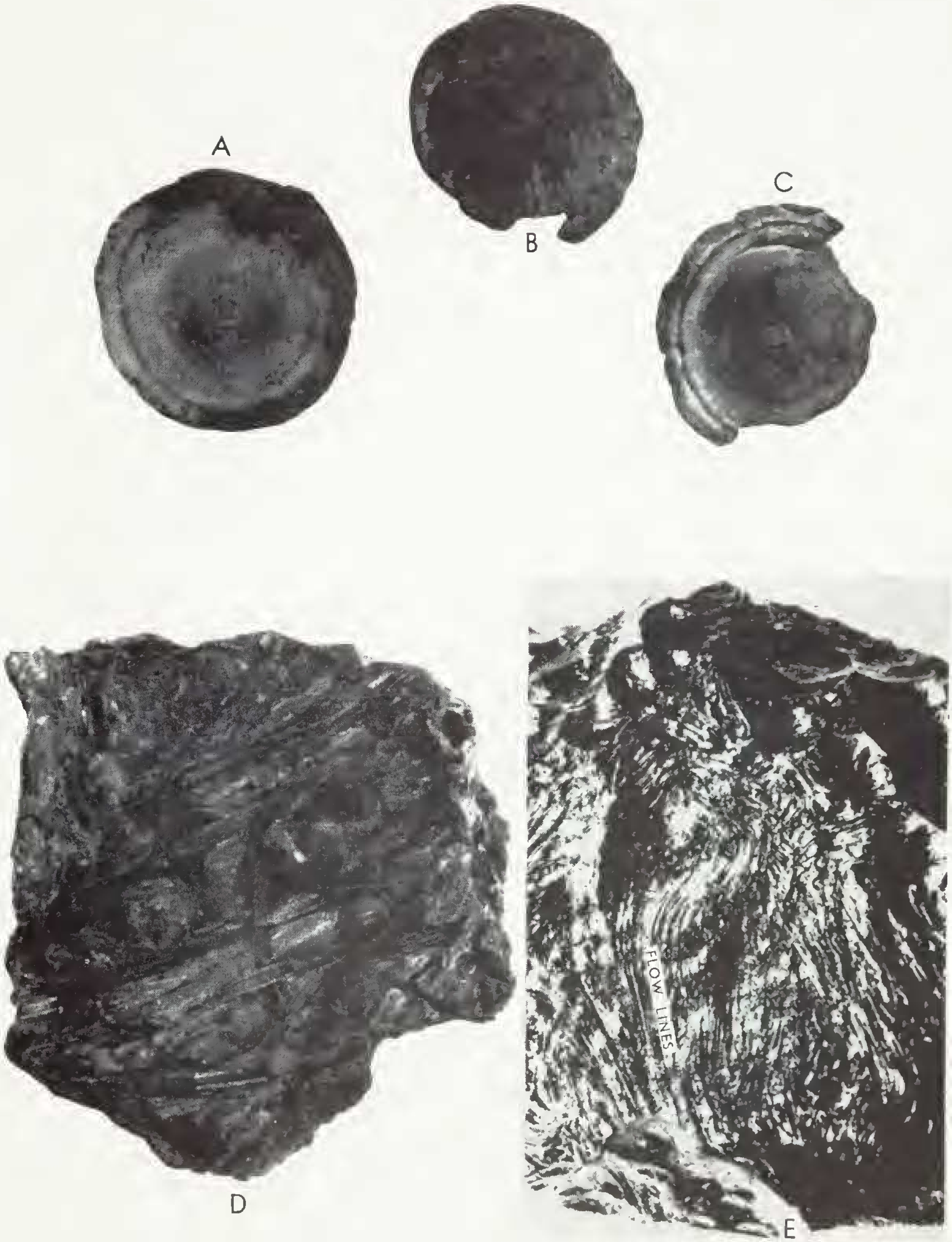


Plate XXI.- Fragments of "pseudo-tektite" glass (actually tachylyte), showing pits, flow grooves, flow lines and "navels" like those on some tektites. No. 1 shows peculiar "ring-marks"; No. 10 is a fragment of abraded, dark coloured artificial glass (broken bottle-neck).

From mouth of Sherbrook River, near Port Campbell, Victoria. All (× 1·5). (Photos. by J. S. Mann.)

PLATE XXI.

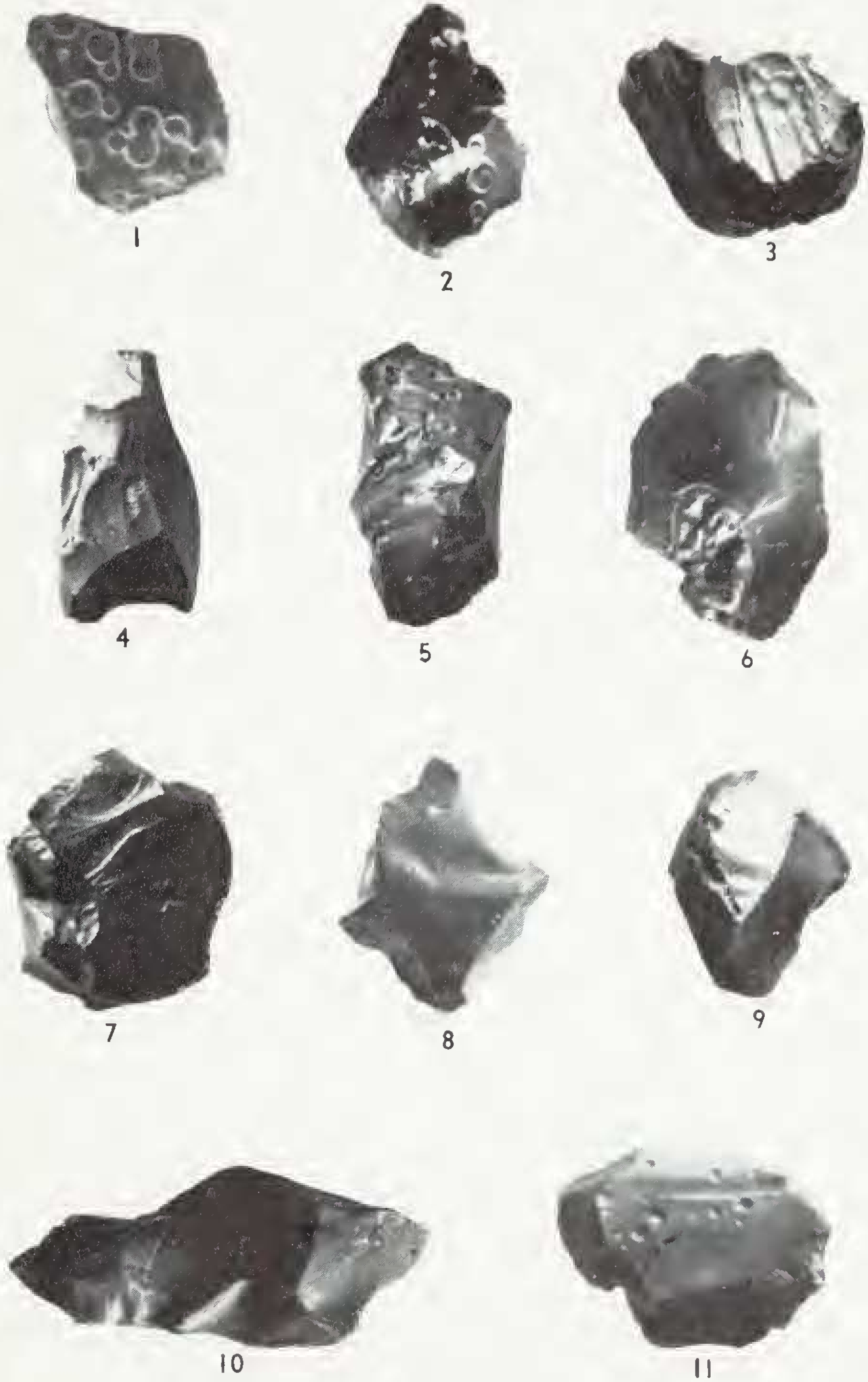


Plate XXII.—External markings formed artificially on colophany, compared with those on the posterior surface of an australite.

A—colophany disc (nat. size) which was rotated at 150 revs./min. for 20 seconds at 22 centimetres from the orifice of a pipe from which steam was forced (after Suess, 1900).

B—external markings on the posterior surface of an australite core of oval outline from Tatyoon, Victoria ($\times$ 2·25) showing some resemblances to artificially produced markings illustrated in A. (Reg. No. 9476 in the geological collection of the Victorian Mines Department.)

(Photos. by J. S. Mann.)

PLATE XXII.

B

A

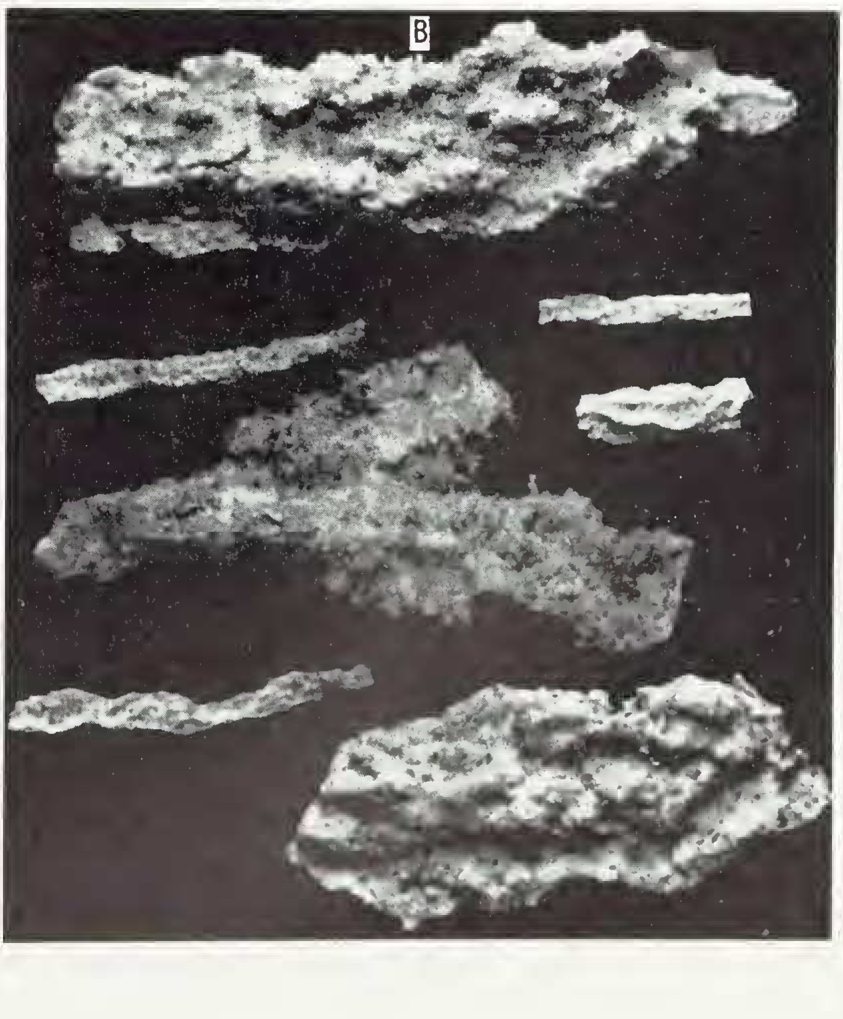
PLATE XXIII.—Darwin Glass and Fulgurites.

A—Darwin Glass (Queenstownite) showing irregular shapes and twisted stalactitic types, from Jukes–Darwin Mining Field, near Mt. Darwin, West Coast, Tasmania (× 1·33).

B—external surfaces of fulgurites showing rugose character (× 1·15). From Macquarie Harbour, New South Wales. (Melbourne University Collection.)

(Photos. by J. S. Mann.)


A


B